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A review on exergy analysis of drying processes and systems

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ABSTRACT

In recent years, growing attention has been given to exergy analysis of drying processes and systems and optimization of drying processes using exergy concept. This research interest is motivated by increasing the price of energies, environmental concerns, world population, decreasing fossil fuel recourses, and demanding for high quality dried products. Exergetic analysis provides a tool for a more realistic view between energy losses to the environment and internal irreversibilities in the process. The present literature review summarizes the using of exergy analysis in drying operations and facilities, discovers it benefits and abilities, and identifies prospects for future researches.

Contents

1. Introduction

The term drying or dehydration refers to removal of moisture from the solid or nearly solid material by evaporation under controlled condition [1]. Drying is perhaps the oldest method and most common form of food preservation employed by humankind [2–5]. It assures the microbial stability and guarantees the expected shelf-life of product; as well as provides the easier handling of product [6,7]. However, nowadays drying is not confined to the food industry. In industrialized world, drying is an essential operation in chemical, agricultural, biotechnology, polymer, ceramics, pharmaceutical, pulp and paper, mineral processing, and wood industries [8].

Traditionally, the Sun's energy was used for drying of agricultural and food products. It is the most widely practiced form of drying in the world because it is cheap, easy, and convenient.

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Nomenclature

Symbols

A	area, m^2
E	emissive power, kJ/s
ex	specific exergy, kJ/kg
$\dot{E}$	energy rate, kJ/s
$\dot{E}x$	exergy rate, kJ/s
F	shape factor
g	gravitational constant, m/s^2
g_c	constant in Newton's law
I	electric current, A
IR	radiation, W/m^2
$I\dot{P}$	improvement potential rate, kJ/s
J	Joule constant
$\dot{m}$	mass flow rate, kg/s
N	number of species
P	pressure, kPa
q	specific heat, J/kg
s	specific entropy, kJ/kg K
T	temperature, K
u	specific internal energy, kJ/kg
υ	specific volume, m^3/kg
V	velocity or voltage, m/s or V
w	specific work, J/kg
W	work rate, J/s
z	altitude coordinate, m

Subscripts

in	inlet
out	outlet
∞	dead state
c	chemical
$dest$	destruction
gen	generated
r	region

Greek symbols

μ	chemical potential, kJ/kg
ψ	exergetic efficiency

Even though Sun drying requires little capital or expertise, but there are many problems in using this method for drying of food products, such as undesirable changes in the quality of food products, being extremely weather dependent, aromas and vitamins loss due to direct sunlight, lack of sufficient control during drying, long drying time, contamination of the product with soil and dust, non-uniformity of dried products, and large space requirements, all of which necessitate using new technology in the drying process [9].

These problems could be overcome if artificial or industrial dryers are used. Nowadays, dryers have an important position in industry for processing and preservation of different foods and industrial material. More than 400 types of dryers have been reported in the literature amongst which solely 50 types are commonly used and readily available from various vendors. Drying is the most energy-intensive industrial unit operation due to the high latent heat of vaporization and the inherent inefficiency of using hot air as the most commonly applied drying medium. It consumes large amounts of energy and releases significant amount of carbon oxides to the environment [8]. Thus, one of the key issues of drying technology is to reduce the cost of energy sources to increase the efficiency of drying facilities for good quality of dried products. On the other hand, the design of an energy-intensive system for lower cost and higher efficiency is one of the essential approaches for sustainable development. Due to the high prices of energy, environmental concerns as acid rain and stratospheric ozone depletion, global warming, increased world population and decreasing fossil fuel recourses, the optimum application of energy and the energy consumption management methods are vital. Energy analysis is a basic and traditional approach to estimate various energy conversion processes [10].

The energy analysis is based on the first law of thermodynamics, which expressed the principle of the conservation of energy. However, it provides no information about the irreversibility aspects of thermodynamic processes. The energy analysis is unable to distinguish the different qualities of energy such as heat quality which is dependent on the heat source temperature. Due to these deficiencies and shortcomings of energy analysis, the exergy analysis which provides a more realistic view of the systems and processes has appeared a more powerful tool for engineering evaluations. Exergy is the maximum amount of work obtainable from a stream of matter, heat or work when some matter is brought to a state of thermodynamic equilibrium with the common components of natural surroundings by means of reversible processes, and is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment [11–14]. The exergy analysis can provide comprehensive and deeper insight into the process and new unforeseen ideas for improvements, and therefore it is applicable for the processes evaluation and optimization purposes. It is however noteworthy that the exergetic performance assessments not only distinguishes the magnitudes, location and causes of irreversibilities in the plants, but also enables the engineers to recognize the individual components efficiency of plant [15,16]. The exergy based performance evaluation and subsequent optimization of drying facilities have been a growing interest among the researchers in recent years. It is noteworthy that the suggested strategies based on exergy concept or energy analysis to improve the system efficiency are quite different. The main objective of exergy analysis of drying systems is to provide a clear picture of the process, to quantify the sources of inefficiency, to distinguish the quality of energy consumption, to select optimal

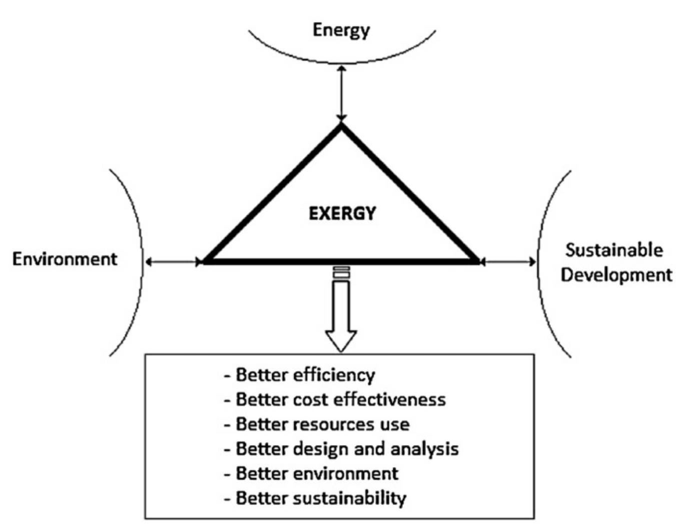

Fig. 1. The interdisciplinary triangle of exergy [17,18].

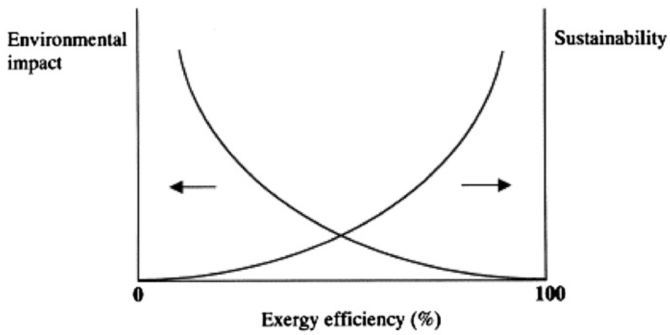

Fig. 2. Qualitative illustration of the relation between the environmental impact and sustainability of a process, and its exergy efficiency [12,13].

drying conditions and to reduce the environmental impact of drying systems. The linkages between exergy and energy, and environmental impact are compressively explained in a triangular Bejan [17] and Dincer and Rosen [18] (Fig. 1).

Fig. 2 illustratively presents the relation between exergy and sustainability and environmental impact [12,13]. It is clear from this figure that increase in exergy efficiency decreases the environmental impact and increases sustainability and vice versa.

According to Mujumdar [8], industrial dryers consume a major counterpart of the total energy (12% on the average) utilized in manufacturing processes. Thus, the drying systems have predominant share in greenhouse gases emission and, as a consequence, in acid rain and stratospheric ozone depletion.

-Currently, a very interesting trend in drying technology is quality enhancement of dried products with lower energy consumption and capital cost using combined exergy and economic concepts, namely exergoeconomics. The exergoeconomics provides a technique to evaluate the costs of inefficiencies or the costs of individual process streams, including intermediate and final products. At the following sections, some aspects of exergy analysis and its applications in drying technology for analyzing and optimization of drying processes are discussed.

2. Exergy analysis

2.1. Exergy concept

The energy, entropy, and exergy concepts stem from thermodynamics and are applicable to all fields of science and engineering. Fig. 3 illustrates a typical view of flow in and out energy, exergy, and entropy through a system [19].

It is clear from this figure that the magnitudes of energy flowing in and out are equal under thermally steady-state condition based on the first law of thermodynamic; on the other hand, the magnitude of entropy flowing out is larger than flowing in because exergy is destroyed within the system to generate entropy. It can be concluded that the energy analysis provides no information about the irreversibility aspects of thermodynamic processes and is therefore useless for design or optimization purposes. Whereas, the exergy analysis of the system gives insight to the inefficiencies and provides opportunities for exergy loss minimization of unit operations.

2.2. Mass, energy, entropy, and exergy balances for drying process and systems

The mass balance equation for a drying system can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

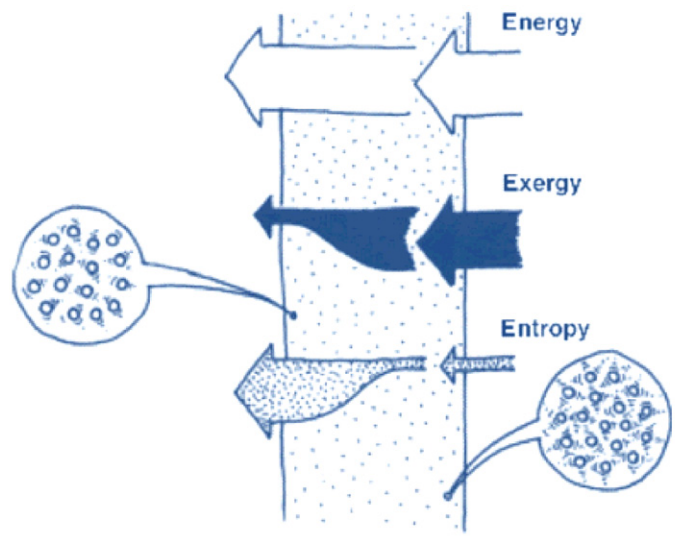

Fig. 3. A schematic view of energy, exergy, and entropy flow in and out a system [19].

Table 1
Specific exergy contents of different energy flows [20].

Type of energy flow	Specific energy	Specific exergy (ex)	Dimension
Kinetic	$\frac{1}{2}v^2$	$\frac{1}{2}v^2$	J/kg
Potential	gz	gz	J/kg
Heat	q	$q\left(1-\frac{T_\infty}{T_q}\right)$	J/kg
Mechanical	W	W	J/kg
Electrical	VIt	VIt	[J]
Chemical, pure substance	$\mu-\mu_\infty$	$\mu-\mu_\infty+RT_\infty \ln\left(\frac{c}{c_\infty}\right)$	J/kg
Radiation	IR	$\sigma\left(T_s^4-\frac{4T_s^3T_\infty}{3}+\frac{T_\infty^4}{3}\right)$	W/m^2

The general energy balance can be expressed below as the total energy inputs equal to total energy outputs

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{2}$$

Energy flows present themselves in nature in different forms and each form has a corresponding exergy value. The most commonly used are listed in Table 1 [20].

The general form of specific exergy equation can be applied for steady flow systems as follows [21,22]:

$$ex = (u-u_\infty) - T_0(s-s_\infty) + \frac{P_0}{J}(\upsilon-\upsilon_\infty) + \frac{V^2}{2gJ} + (z-z_\infty)\frac{g}{g_c J} + \sum_c (\mu_c-\mu_\infty)N_c + E_g A_g F_g (3T^4 - T_\infty^4 - 4T_\infty T^3) + \cdots \tag{3}$$

The general exergy balance can be expressed in the rate form as [23]

$$\sum \left(1-\frac{T_\infty}{T_k}\right)\dot{Q}_k + \sum \dot{E}x_{in} = W + \sum \dot{E}x_{out} + \dot{E}x_{dest} \tag{4}$$

$$\sum \left(1-\frac{T_\infty}{T_k}\right)\dot{Q}_k + \sum \dot{m}_{in} ex_{in} = W + \sum \dot{m}_{out} ex_{out} + \dot{E}x_{dest} \tag{5}$$

The general entropy balance can be written as follows:

$$\dot{S}_{gen} = \sum \dot{m}_{in} s_{in} - \sum \dot{m}_{out} s_{out} \pm \sum \frac{\dot{q}_r}{T_r} \tag{6}$$

where the negative sign in last term denotes the amount of heat transferred into the control volume and positive sign denotes the amount of heat transferred from the control volume across region r on the control surface. Also, the generated entropy can be

calculated using following equation:

$$\dot{E}x_{dest} = T_0 \dot{S}_{gen} \tag{7}$$

The exergy efficiency of drying chamber or rational exergy efficiency can be calculated using the following equation [12,24]:

$$\psi = \frac{Ex_{out}}{Ex_{in}} \times 100 \tag{8}$$

Also, Dincer and Sahin [25] defined exergy efficiency of the drying process as the ratio of exergy use (investment) in the drying of the product to exergy of the drying air supplied to the system

$$\psi = \frac{exergy\ investment\ in\ the\ evaporation\ of\ moisture\ in\ the\ product}{exergy\ of\ drying\ air\ supplied} \times 100 \tag{9}$$

Van Gool [26] proposed that maximum improvement in the exergy efficiency for a process or system is obviously achieved when the exergy loss or irreversibility ($Ex_{in} - Ex_{out}$) is minimized. Consequently, he suggested that it is useful to employ the concept of an exergetic "improvement potential" when analyzing different processes or sectors of the economy. This improvement potential in the rate form, denoted $I\dot{P}$, is given by

$$I\dot{P} = (1-\psi)(Ex_{in} - Ex_{out}) \tag{10}$$

The improvement potential has been used by many researchers to find the potential of drying process or drying chamber to enhance exergy efficiency.

3. Application of exergy analysis to the drying process and facilities

Exergy analysis of drying process and systems can be categorized based on different aspects. One grouping can be derived from the dryers' classification criterions including mode of operation, heat input-type, state of material in dryer, operating pressure, drying medium, drying temperature, relative motion between drying medium and drying solids, number of stages, and residence time [8]. It is mentioned that the categorization of dryer systems is not entirely scientific but also includes subjective judgment as well as remarkable empiricism. In this review, the exergy analysis of drying systems is classified to seven different categories based on published work: batch or tray drying, continuous or industrial drying, heat pump assisted drying systems, fluidized bed drying, solar drying, freeze drying, spray drying, vacuum drying, and flash drying.

3.1. Batch or tray drying

Tray dryers are the most extensively applied dryers for small tonnage products. A tray dryer is consisted of a stack of trays or several stacks of trays located in a large insulated chamber in which hot air is blown with properly designed fans and guide vanes. Recalculating the known amount of the exhausted air with a fan located within or outside the drying chamber is usually employed. The uniform air flow distribution over the trays is required for successful operation and it determines the dryer capacity and the residence time of product [8]. The range of drying medium temperature, domain of mass flow rate of drying media, type of drying media (air, nitrogen, steam, etc.), capacity of dryer, number of trays, distance between trays, and type of heater (electrical, fuel-powered, etc.) are the most important design parameters of tray dryer. Table 2 summarizes some of the recent studies and the most important results obtained using exergy analysis to evaluate the tray or batch dryers' performance.

Dincer and Sahin [25] took into account three components including product itself, air and the water which exits in the

Table 2
Some of the recent studies and the most important results obtained using exergy analysis to evaluate the tray or batch dryers' performance.

Author(s): Dincer and Sahin [25]
Dryer type: Hot air dryer
Product(s): Assumptive
Aim: To introduce a new model for energy and exergy analyses of drying process
Experimental or simulation variable(s): T=55–100 °C, RH=10–35%, MFDA=0–2.5 kg/s, and MFP=2.778×10^{-4}–5.5556×10^{-3} kg/s
Outcome: Exergy efficiency of drying process decreased with increasing drying air temperature, drying air mass flow rate, and humidity ratio of drying air. However, exergy efficiency of drying process increased with increasing product mass flow rate

Author(s): Akpinar [21]
Dryer type: Laboratory tray dryer
Product(s): Red pepper slices
Aim: To find the effect of drying air temperature on energy and exergy analyses.
Experimental or simulation variable(s): T=55–70 °C and V=1.5 m/s.
Outcome: Exergy efficiency of drying chamber varied between 67.28 and 97.92% at the studied drying air temperature

Author(s): Akpinar [22]
Dryer type: Hot air cyclone dryer
Product(s): Eggplant slices
Aim: To study the effect drying air temperature and velocity on energy and exergy analyses
Experimental or simulation variable(s): T=55–75 °C and V=1.0–1.5 m/s
Outcome: Exergy efficiency of drying chamber at different drying conditions varied between 43.34 and 100%

Author(s): Akpinar et al. [27]
Dryer type: Two-tray hot air cyclone dryer
Product(s): Potato slices
Aim: To elucidate the effect of drying air temperature, drying air velocity, and tray order on energy and exergy analyses
Experimental or simulation variable(s): T=60–80 °C, V=1–1.5 m/s, RH=10–20%, and tray order
Outcome: The exergy efficiency for first tray, second tray, and overall drying systems was 27.48–100%, 10.98–100%, and 3.17–100%, respectively. Generally, the exergy efficiency was higher for the first tray compared with the second one

Author(s): Akpinar et al. [28]
Dryer type: Two-tray hot air cyclone dryer
Product(s): Apple slices
Aim: To perform the energy and exergy analyses for drying cabinet
Experimental or simulation variable(s): T=60–80 °C, V=1.5 m/s, RH=10–20%, and tray order
Outcome: The calculated exergy efficiency values were 57.66–100%, 55.50–100%, and 32.00–100% for the first tray, second tray, and overall drying duct, respectively. The exergetic efficiency of the first tray was higher than that of the second tray and drying chamber

Author(s): Akpinar et al. [29]
Dryer type: Two-tray hot air cyclone dryer
Product(s): Pumpkin slices
Aim: To employ the first and second law of thermodynamics for hot air drying system
Experimental or simulation variable(s): T=60–80 °C, V=1–1.5 m/s, RH=10–20%, and tray order
Outcome: The exergy efficiency was found to be in range of 50.47–100%, 38.44–100%, and 19.40–100% for the first tray, second tray, and overall drying chamber, respectively. Generally, the exergy efficiency for the second tray was lower than the first tray

Author(s): Akpinar [30]
Dryer type: Experimental tray dryer
Product(s): Strawberry slices
Aim: To study the variation of energy and exergy during hot air drying
Experimental or simulation variable(s): T=60–85 °C and V=0.5–1.5 m/s
Outcome: Exergetic efficiency of drying system was found to be in range of 24.81–100%. Exergy efficiency increased with progressing drying time, increasing drying air temperature, and drying air velocity

Author(s): Colak and Hepbasli [31]
Dryer type: Experimental tray dryer
Product(s): Green olive
Aim: To analyze the hot air drying of green olive using exergy analysis method

Table 2 (*continued*)

Experimental or simulation variable(s): T=40–70 °C, MFDA=0.01–0.015 kg/s, and MFP=$1.5\times10^{-4}-9.0\times10^{-4}$ kg/s
Outcome: The exergy efficiency of drying chamber values was found to be in the range of 68.65–91.79% for the examined drying conditions

Author(s): Vaughan et al. [32]
Dryer type: Dehumidifier dryer
Product(s): Wood-stack
Aim: To utilize the exergy loss and entropy generation methods for assessing the irreversibility in wood drying
Experimental or simulation variable(s): T=30–80 °C, V=0.5–9 m/s, RH=20–95%, sticker size=0.01–0.04 m, and stack alignment (vertically aligned, horizontally aligned or staggered)
Outcome: Exergy destruction and entropy generation rates increased with increasing the sticker size, drying air temperature, and drying air velocity and decreasing the relative humidity. Generally, exergy destruction for the horizontal alignment was the highest at different simulation ranges, whereas for the vertical alignment was the lowest

Author(s): Corzo et al. [33]
Dryer type: Laboratory tray dryer
Product(s): Coroba slices
Aim: To assess the effect of drying air temperature and velocity on energy and exergy analyses
Experimental or simulation variable(s): T=71–93 °C and V=0.82–1.18 m/s
Outcome: The values of exergy efficiency of drying chamber were found to be in the range of 80–97% for the investigated drying conditions

Author(s): Corzo et al. [34]
Dryer type: Laboratory tray dryer
Product(s): Coroba slices
Aim: To optimize the drying condition based on drying, energy, and exergy concepts
Experimental or simulation variable(s): T=71–93 °C and V=0.82–1.18 m/s
Outcome: The optimum conditions were: T=90.6 °C, t=69 min, and V=1.08 m/s in order to obtain MC=0.3815 g/g, DR=0.000103 g water/g s, energy efficiency equal 0.785%, and exergy efficiency equal 90.9%

Author(s): Erbay and Icier [35]
Dryer type: Laboratory tray dryer
Product(s): Olive leaves
Aim: To optimize the operating conditions of the drying of olive leaves in a tray drier according to the drying, exergy, and quality parameters
Experimental or simulation variable(s): T=40–60 °C, V=0.5–1.5 m/s, and t=240–480 min
Outcome: The optimum condition was found to be the T=51.16 °C with the V=1.01 m/s for the t=298.68 min. At this optimum point, total phenolic content loss, total antioxidant activity loss, moisture content, and exergy efficiency were found as 10.25, 41.88, 6.0 and 65.50%, respectively

Author(s): Fortes et al. [36]
Dryer type: Experimental deep bed dryer
Product(s): Corn
Aim: To simulate the energetic and exergetic performance of deep bed drying process using one-dimensional solution of momentum, heat, mass, and entropy generation equations
Experimental or simulation variable(s): T=30–37 °C, V=0.2–0.6 m/s, MC= 0.25–0.33 (db)
Outcome: The results were acceptable for predicting the energetic and exergetic performance of deep-bed drying process

Author(s): Erbay and Icier [37]
Dryer type: Experimental hot air dryer
Product(s): Olive leaves
Aim: To evaluate the effects of the drying air temperature and drying air velocity on exegetic performance of drying cabinet
Experimental or simulation variable(s): T=40–60 °C and V= 0.5–1.5 m/s
Outcome: The exergetic efficiency of drying cabinet varied between 55.95 and 75.12% for the surveyed conditions

Author(s): Hancioglu et al. [38]
Dryer type: Laboratory tray dryer
Product(s): Parsley
Aim: To seek the effect of drying air temperature and drying air velocity on energy and exergy efficiencies of drying process as well as overall exergy efficiency of drying system
Experimental or simulation variable(s): T=40–60 °C and V=0.5–1.5 m/s
Outcome: The exergy efficiency of overall system based on process efficiency was found to 3.6% at drying temperature of 50 °C, drying air velocity of 1 m/s, and dead-state temperature of 14.7 °C. Drying air temperature had significant influence on the exergy efficiency of drying process. Whereas increasing drying air velocity did not lead to a profound effect on the exergy efficiency of drying process

Author(s): Icier et al. [39]
Dryer type: Experimental tray dryer
Product(s): Broccoli Florets
Aim: To compare the exergetic performance of drying chamber and drying process for three different types of hot air dryer including: tray dryer, fluidized bed dryer, and heat pump dryer
Experimental or simulation variable(s): T=50–70 °C and V=0.5–1.5 m/s for tray dryer
Outcome: The exergy of efficiency of tray drying chamber varied between 59.70 and 81.92%, whereas the exergy efficiency of drying process was found to be in range of 8.2 and 15.9%

Author(s): Hepbasli et al. [40]
Dryer type: Experimental tray dryer
Product(s): Plum slice
Aim: To compare the exergetic performance of whole systems for three different types of convective dryers including: tray dryer, fluidized bed dryer, and heat pump dryer
Experimental or simulation variable(s): T=45–55 °C and V=0.5–1.5 m/s for tray dryer
Outcome: The exergy efficiency of fan, heater, and whole tray dryer system was found to be in rang of 93.97–95.49%, 24.07–25.53%, and 37.93–39.45%, respectively

Author(s): Prommas et al. [41]
Dryer type: Laboratory convective dryer
Product(s): Glass beads
Aim: To investigate the effect of bed configuration on energy and exergy analyses in convective drying process of multi-layered porous media
Experimental or simulation variable(s): T=70 °C, V=1.2 m/s, particle diameter= 0.15 and 0.4 mm (fine and coarse, respectively), and bed configuration: fine (40 mm of bed height), coarse (40 mm of bed height), fine-coarse (20–20 mm of bed height), and coarse-fine bed height (20–20 mm of bed height)
Outcome: Exergy efficiency of drying chamber for the drying of coarse-fine configuration was highest which followed by coarse, fine, and fine-coarse configuration, respectively

Author(s): Prommas et al. [42]
Dryer type: Laboratory convective dryer
Product(s): Glass beads
Aim: To survey the effect of particle size on energy and exergy analyses
Experimental or simulation variable(s): T=50 °C, V=2.5 m/s, and particle diameter= 0.15 and 0.45 mm (fine and coarse, respectively)
Outcome: Exergy efficiency of drying chamber for drying of the fine particle was higher than drying of the coarse particle

Author(s): Akpinar [43]
Dryer type: Convective cyclone dryer
Product(s): Apple slices
Aim: To perform an exergy analysis associated with the transient heat transfer and employ a new factor combing the second law of thermodynamics and heat transfer parameters namely exergetic heating effectiveness
Experimental or simulation variable(s): T=60–80 °C and V=1.0–1.5 m/s
Outcome: The exergy efficiency and exergetic heating effectiveness varied between 35 and 100% and 0 and 0.96, respectively

Author(s): Karimi and Rafiee [44]
Dryer type: Laboratory hot dryer
Product(s): Lavender leaves
Aim: To examine the estimation and optimization capabilities of artificial neural network and response surface methodology for drying process based on moisture content, drying rate, energy and exergy efficiencies
Experimental or simulation variable(s): T=33–67 °C, V=0.4–1.4 m/s, and t=3.96–14.04 h
Outcome: The optimum drying condition based on artificial neural network approach was T=46.8 °C, V=0.726 m/s, and t=9.72 h and responses were: MC=0.32 g/g, DR=0.29 g water/g h, energy efficiency of 67% and exergy efficiency 80%

Author(s): Karimi et al. [45]
Dryer type: Laboratory hot dryer
Product(s): Artemisia absinthium leaves
Aim: To apply the back-propagation artificial neural network and response surface methodology to optimize drying condition based on drying, energy, and exergy concept
Experimental or simulation variable(s): T=33–67 °C, V=0.4–1.4 m/s, and t=3.96–14.04 h

Table 2 (*continued*)

Outcome: The optimum operating conditions obtained from the artificial neural network model was: T=47.3 8 °C; V=0.906 m/s and t=10.35 and correspond MC=0.15 g/g, DR=0.35 g water/(g h), energy efficiency= 73%, and exergy efficiency=85%
Author(s): Motevali and Minaei [46] Dryer type: Laboratory hot air dryer Product(s): Sour pomegranate Aim: To investigate the effect microwave pretreatment on energy utilization ratio and exergy efficiency of drying chamber Experimental or simulation variable(s): T=50–70 °C, V=0.5–1.5 m/s, and pretreatments: control treatment, 100 W microwave power for 20 min, and 200 W microwave power for 10 min Outcome: Exergy efficiency of drying chamber varied between 44.85–100%, 62.54–100%, and 73.68–100% during drying of control treatment, 100 W microwave power for 20 min pretreated samples, and 200 W microwave power for 10 min pretreated samples, respectively

T: drying air temperature, V: drying air velocity, MFDA; mass flow rate of drying air, MFP: mass flow rate of product, t: drying time, MC: moisture content, DR: drying rate.

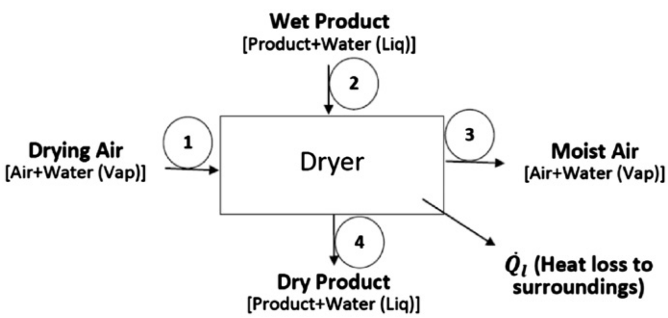

Fig. 4. Schematic of drying process with input and output terms [25].

drying air and product to write the mass balance equations (Fig. 4). The exergy efficiency derived as functions of heat and mass transfer parameters and the model was applied for an illustrative example. The applicability of the presented model for actual drying processes at different drying air temperatures, specific exergies of drying air, exergy differences of inlet and outlet products, product weights, moisture contents of drying air, and humidity ratios of drying air was proved. The exergy efficiency was defined based on process usefulness i.e. the amount of supplied exergy was productivity utilized for moisture evaporation from products being dried. Thus, the application of this definition can lead to conceptual and meaningful results. It is worth noting that this model can be successfully employed for a wide range of drying methods by some modifications. Recently, Dincer [13] modified the definition of exergetic efficiency of drying process by taking into account the outlet exergy from drying chamber and exergy employed for heating of materials being dried. It is however notable that the suitability of new definition for the actual drying process should be further ascertained by experimental investigations.

Akpinar et al. [27–29] found that the exergy efficiency of drying duct increased with drying time and was high for high drying air temperature and velocity. As well as, the exergy efficiency for first tray was considerably higher than second one. The exergy inflow values to the first tray were equal to those into the drying chamber; whilst, the values of exergy inflow to the second tray were equal to those of the exergy outflow from the first tray. Not only the values of exergy losses of the first tray were higher than those of the second tray but also the values of exergy inflow to the first tray were higher than those of the second tray. These in turn led to higher exergetic efficiency of the first tray compared with the second tray. As well, in the hot air drying of potato slices it was observed that the exergy efficiency of dryer had descending form in primary stage of drying time due to the initial heating up of products and then ascending form toward to the end of drying process due to second drying step (falling rate period).

Akpinar [21,22,30] observed that the exergy efficiency of dryer heightened with progressing drying time and increasing drying air temperature and air velocity, as previously explained. The exergy efficiency of drying chamber was inversely proportional to the moisture content of product and increased with removing water from the samples. Therefore, the exergy utilization for moisture evaporation from the product exponentially diminished toward to the end of drying process with a trend similar to the drying kinetics. Generally, it can be inferred that the major part of supplied exergy to drying chamber wasted by exhausted air. Therefore, the conscious strategy is required to reuse this large amount of exhausted exergy.

Colak and Hepbasli [31] showed that the exergy efficiency of dryer increased linearly with increasing drying air temperature, drying air mass flow rate, and feed mass flow rate. The exergy efficiency was profoundly influenced by drying air temperature which followed by drying air mass flow rate and feed mass flow rate. The exergetic efficiency of drying chamber was considerably high indicating that the outflow drying air had a good potential for further drying. The exergy lost through the drying chamber was remarkably heightened with the augmentation of boundary temperature of the drying frame. It should be noted that the simple and low-cost thermodynamic modifications such as increasing the uniformity of air velocity and temperature distribution in the bulk would be feasible for increasing exergy efficiency of drying process and decreasing operating costs.

Vaughan et al. [32] indicated that the entropy generation method was broadly consistent over the exergy destruction approach for computing the exergy destruction in wood drying. The heat transfer had a predominant effect on the entropy generation and the corresponding overall irreversibility, while the momentum transfer and mass transfer stood in second and third ranks, respectively. The exergy loss was profoundly influenced by air stream, sticker size, and side-stack configuration. The use of lower temperatures and velocities and higher relative humidities was proposed as ways for reducing the exergy destruction by rebating the heat and mass transfer. Finally, the stack design parameters for minimizing the overall exergy destruction rate were determined. It can be concluded that the heterogeneous nature of wood stack and subsequent complex and dynamic temper of its thermal properties may terminate to a drastic dependency of exergy destruction in wood drying to the drying air velocity and temperature distributions, drying medium direction relative to wood, wood type, wood configuration, etc.

Corzo et al. [33,34] reported the exergy efficiency of dryer decreased with increasing drying time, while increased with increasing drying air temperature and air velocity. The decreasing exergy efficiency with advancing in drying time can be interpreted in the same way as previously explained for potato convective drying [27]. The exergy efficiency was high at the primary stage of drying process while it continually decreased by progressing drying time. The outflow exergy from dryer, the exergy loss to ambient through the dryer chamber, and the exergy of material were identified as major contributors to the thermodynamic inefficiencies of dryer. In the second study, moisture content, drying rate, energy efficiency, and exergy efficiency of product subjected to hot air drying successfully modeled and optimized by RSM approach. The RSM and the conventional graphic and desirability functions methods were found to be effective in determining the optimum zone within the

experimental region or space used for the drying of foodstuff. However, it is notable that the increasing the sustainability of a process using the exergy approach may negatively influence the quality of dried product and even lead to its deterioration. In the case of foodstuff drying, the quality importance becomes even more pronounced due to human health. Therefore, the physiochemical attributes of foods should be considered for selecting an optimal drying condition.

Fortes et al. [36] ascertained the suitability of transient and spatial energy and exergy analyses model by one-dimensional numerically solving of the mass, energy, momentum, enthalpy, and entropy balance equations for deep-bed grain drying using radial basis function (RBF) method. The validation results of the model, tested by Brooker data [47], were not published. However, authors claimed that the numerical solution had an excellent accuracy by comparing the model output with the data available in literature. It was suggested to add a rewetting equation coupled with the corn kernel drying equation to improve the prediction ability of the model. It is interesting to note that the numerical approach for the evaluation of exergetic efficiency of drying process not only avoid the high-cost experimental operation but also eliminate the instrument uncertainties. However, the development of numerical models to compute the exergetic performance of drying process with an adequate precision merits further investigations.

Erbay and Icier [35] found that the lower drying air temperature, higher drying air velocity, and longer process time were required to enhance the exergy efficiency of drying system. The insufficient isolation and airproof in the tray dryer were mentioned as main reasons for increasing the heat loss from drying chamber and correspondingly decreasing the exergetic efficiency of drying duct. The effect of drying air temperature on heat losses and irreversibilities was dominant over the effect of air velocity. The capability of RSM for modeling and integrating the dryer's exergetic performance with the quality of dried product was demonstrated. In addition, the optimization procedure using the exergetic efficiency of process and other optimization techniques can lead to the more comprehensive and meaningful results.

In accordance with the findings of previous investigations, Prommas et al. [41,42] observed that the exergy efficiency of dryer increased with drying time. The exergy efficiency of drying chamber was strongly depended on particle size and multi-layered configurations. Increasing the exergy efficiency of dryer with progressing drying was interpreted by increasing available energy in the drying chamber as result of moisture evaporation. It can be concluded that the heat and mass transfer are the main parameters affecting the thermodynamics performance of tray dryer. Thus, additional studies are awaited to correlate the exergetic performance of tray drying process to heat and mass transfer parameters.

In another study on tray dryer, Hancioglu et al. [38] reported that the energy efficiency was higher than the exergy efficiency. It was demonstrated that the exergy is a measure of quality of energy and it can clearly consider the loss of availability of heat in the drying systems. Therefore, the exergetic performance assessments of thermal systems can became a vital analysis of high energy-consuming thermal systems such as drying equipments. Results also showed that the higher drying temperature and lower drying air velocity led to higher exergy efficiency of drying tray. The higher drying air temperature and lower drying air velocity should be employed for drying of parsley from energetic, economic, and environmental points of view. The overall exergetic efficiency of dryer based on process efficiency was very small indicating that the masterly plans are needed to improve the second law performance of most commonly employed hot air dryer.

Akpinar [43] carrying out an exergy analysis associated with the transient heat transfer using the Dincer and Dost's [48] analytical technique, observed that the exergetic heating effectiveness increased with drying time, drying air temperature, and drying air velocity similar with the exergy efficiency of drying system. However, the capability of presented parameters for actual drying systems and processes has not been clearly identified. Thus, in order to verify the capabilities of introduced parameters and to correlate it with exergetic efficiency of drying process, new studies need to be carried out to meet real-world requirements.

Icier [39] found that the exergy efficiency of drying chamber in fluidized bed approach somewhat higher than the exergy efficiency of drying chamber in tray and heat pump methods. When the exergy efficiency was computed based on product to fuel definition as the rate of evaporation exergy to the rate of drying air exergy entering to the drying chamber, it was found that exergy efficiencies of dryer were significantly higher than that of drying process. The lower amount of exergy utilized for water evaporation from samples being dehydrated was the main reason responsible for this small exergy efficiency of process. Nevertheless, this definition could lead to more meaningful, objective, and useful results and conclusions to assess the performance of the drying process relative to the performance of drying chamber.

In a another study, Hepbasli et al. [40] found that the best way to improve the tray dryer efficiency was to recycle the outlet drying air since approximately one-fourth of the exergy inflow was thrown away as waste exergy. The recycling of outflow air was also proposed as way to improve the fluidized bed dryer efficiency, but its importance was not so much as compared to the tray dryer. Consequently, it was authenticated that the heat pump systems were efficient and could be used or integrated to the energy-intensive drying systems to elevate their exergy efficiency. It is worth noting that the determining factor to select an exergetic efficient drying system is overwhelmingly cost-related which can be evaluated using the exergoeconomic analysis.

According to Erbay and Icier [37], the exergetic efficiency of drying tray decreased with increasing the drying air temperature and decreasing the drying air velocity. The effect of drying air temperature on exergy was predominant than the effect of drying air velocity. Increasing dead-state (reference) temperature decreased the exergy efficiency of dryer while increasing dead-state humidity ratio did not lead to a known trend with the exergy efficiency. The insulation of drying chamber was motioned to improve the exergetic performance of tray dryer especially for higher drying air temperatures. Furthermore, it was determined the dead (reference) state conditions should carefully be set to the reference environment to obtain appropriate results.

Motevali and Minaei [46] found that the increasing drying air temperature and drying air velocity increased the exergy efficiency of drying chamber for both control and microwave pretreated samples. The exergy efficiency of drying chamber increased with drying time and was remarkably higher for drying of the microwave pretreated samples than the control ones. However, in the absence of an appropriate equation for incorporating the microwave exergy into the calculations, it is very controversial to judge about the positive effect of microwave pretreatment on exergy efficiency of drying chamber and process. As well as, the effect of microwave pretreatment on initial moisture content of samples should be considered in the exergetic computation. Generally, it is concluded that the pretreatments of material being dried including microwave, ultrasound, blanching, chemical, etc., can be utilized as way for increasing the exergy efficiency of drying process by taking into account the final product quality.

Karimi and Rafiee [44] and Karimi et al. [45] reported the back-propagation artificial neural network (ANN) has an acceptable potential to find an optimal drying condition according to drying, energy, and exergy concept when it compared with RSM approach. The minimizing of drying time and maximizing of drying air temperature should be considered to maximize the exergy efficiency of drying chamber. It should be noticed that the medicinal plants are collocations of volatile components negatively influencing by severe drying condition. Therefore, an exclusive strategy must be employed during performing an exegetic optimization for drying of aromatic plants.

3.2. Continuous or industrial drying

The batch tray drying method has many advantages for removing moisture from products including simple and low cost chamber, low labor costs, and easy loading and unloading procedure. However, continuous dryers provide higher efficiency than trays, better and more consistent product quality with lower energy consumption [7]. The design parameters for continuous dryers are drying air temperature, drying air mass flow rate, feed mass flow rate, number of stages and passes, air direction relative to feeding orientation (cross-flow, concurrent-flow, countercurrent-flow, and mixed-flow), type of heater, type of drying media, control systems (feedback control, feedforward control, Fuzzy logic (expert) controllers, etc.), capacity of dryer, etc. It should be noted that most of the industrial drying systems are fed in continuous form. Therefore, comprehensive investigations are necessitated on the evaluation of exergetic performance of continuous dryers. As summarized in Table 3, there are in the literature many applications of exergetic analysis to identify locations, kinds and true magnitudes of wastes and losses exergy in continuous or industrial dryers.

Topic [49], surveying the exergetic performance of the high temperature industrial hot air dryer components for the nominal mode of operation as function of the moisture content of input material, reported that the exergy efficiency of mixing bowl intensified significantly by increasing the moisture content. However, the exergy efficiency of dryer and overall system was slightly increased by increasing the moisture content. The dryer second law efficiency was considerably lower than the mixing bowl, furnace, and overall systems. It could be attributed to the higher entropy generation in drying process due to higher heat and mass transfer resulted from higher drying air temperature. Therefore, increasing the drying air temperature to accelerate the water evaporation from materials being dried is not thermodynamically justified due to higher exergy destruction.

Holmberg and Ahtila [50] employed the heat consumption and the irreversibility rate for energy and exergy analyses, respectively. The irreversibility rate is depended on the temperature of the heat source as well as the drying system to a large extent. The irreversibility decreased toward to the last stage, while there was no clear trend for heat consumption. A higher temperature difference between the heat source and air also increased the irreversibility rate. The lower feasible drying temperature and small temperature differences were suggested to decrease the value of the irreversibility rate. It seems that the use of multi-stage dryer with air recycling systems by taking into account the economic considerations can be proposed as ways for decreasing the irreversibility of industrial dryers and lowering the environmental impact of this energy-intensive operation.

The proposed model by Dincer and Sahin [25] was applied to calculate the energy and exergy losses of industrial pasta drying process and system [51]. Heat loss through the dryer's walls due to air leakages was the most important component in the total exergy loss. The next largest contributions to total exergy loss

Table 3
Recent exergy analysis applications in continuous or industrial dryers.

Author(s): Topic [49]
Dryer type: High temperature industrial hot air dryer
Product(s): Forage
Aim: To present a mathematical model for exergy analysis of an industrial high-temperature forage dryer
Experimental or simulation variable(s): Actual drying condition
Outcome: The exergy efficiency of mixing bowl increased with increasing moisture content of product. However, the exergy efficiency of dryer, furnace, and overall system was almost constant with moisture content

Author(s): Holmberg and Ahtila [50]
Dryer type: Single-stage and multi-stage industrial dryer
Product(s): Biofuel
Aim: To calculate and compare the energy efficiency of two different drying processes (single-stage and multi-stage) using two evaluation methods including specific heat consumption and irreversibility rate
Experimental or simulation variable(s): drying media (steam at a pressure of 3 bar and temperature of 133 °C and water at a temperature of 80 °C), single-stage and multi-stage dryer, air recycle ratio, and number of stage
Outcome: The irreversibility rate for the steam media and single stage drying were higher than the water media and multi-stage drying. The irreversibility rate in both drying systems decreased constantly as the values of recycle ratio and number of drying stages increased

Author(s): Ozgener and Ozgener [51]
Dryer type: Industrial hot dryer
Product(s): Pasta
Aim: To compute the energetic and exergetic performance of industrial final macaroni drying process for its system analysis using actual system data
Experimental or simulation variable(s): $T=$ 49.9 °C, $V_{in}=1.1$ m/s, and $V_{out}=5.2$ m/s
Outcome: The exergy efficiencies of drying chamber and whole system were found between 72.98–82.15% and 41.90–70.94%

Author(s): Ozgener [52]
Dryer type: Industrial hot dryer
Product(s): Pasta
Aim: To perform an exergoeconomic analysis of an industrial pasta final drying process
Experimental or simulation variable(s): $T=$ 48–49.9 °C, $V_{in}=1.1$ m/s, and $V_{out}=5.2$ m/s
Outcome: The exergy efficiency of the overall system was found to be as 65.4%. The ratio of exergy loss rate to capital cost was 0.004 (kW/USD)

Author(s): Cay et al. [53]
Dryer type: Stenter
Product(s): Textile
Aim: To study the energetic and exergetic performance of a stenter system in a textile finishing factory based on actual operational data
Experimental or simulation variable(s): Actual drying condition
Outcome: The exergetic efficiencies of the stenter and hot oil boiler were found to be 28.7 and 34.7%, respectively, while the overall exergy efficiency of the system was found to be 34.4%

Author(s): Aghbashlo et al. [54]
Dryer type: Semi–industrial continuous band dryer
Product(s): Potato slices
Aim: To present the energy and exergy analyses of the continuous-convection drying of potato slices
Experimental or simulation variable(s): =50–70 °C, MFDA=0.61–1.83 kg/s, and FP=2.31×10^{-4}–3.48×10^{-4} kg/s
Outcome: The exergy loss and exergy efficiency were found to be in the range of 0.5987 to 13.71 kJ/s and 57.13 to 94.05%

Author(s): Ozgener and Ozgener [55]
Dryer type: Industrial hot dryer
Product(s): Pasta
Aim: To seek the effect of dead-state temperature on exergetic performance
Experimental or simulation variable(s): $T=$ 49.9 °C, $V_{in}=1.1$ m/s, $V_{out}=5.2$ m/s, $T_0=5$–25 °C
Outcome: The energy efficiency was remarkably higher than the exergy efficiency. The exergy efficiency had a linear relation ($\psi=-0.012T_0+0.6755$) with dead-state temperature and slightly decreased from 67.08 to 64.79% with increasing dead-state temperature

Author(s): Coskun et al. [56]
Dryer type: Industrial drum dryer
Product(s): Wood chip

Table 3 (*continued*)

Aim: To assess the performance of an industrial wood chips drying process based on energy and exergy analyses and study how its operating conditions and efficiency can be improved further
Experimental or simulation variable(s): $T=$ 466 °C, MFDA=81.53 kg/s
Outcome: Energy and exergy efficiencies of the drying process were found as 34.07 and 4.39%, respectively

Author(s): Cay [57]
Dryer type: Industrial belt dryer
Product(s): Textile
Aim: To carry out the exergetic analysis of the continuous textile dryer consisting of a stenter and a conveyor belt dryer as function of exhaust humidity ratio
Experimental or simulation variable(s): $T=$150–160 °C
Outcome: The exergetic efficiency of stenter and conveyor belt dryer was found to be 13.7 and 14.3% for the exhaust humidity ratio of 0.1 kg water/kg dry air. The exergy efficiency increased with increasing the exhaust air humidity ratio for both stenter and conveyor belt dryer and correspondingly the exergy destruction decreased. The exergetic efficiency linearly increased with increasing dead-state temperature for both stenter and conveyor belt dryer

Author(s): Aghbashlo et al. [7]
Dryer type: Semi-industrial continuous band dryer
Product(s): Carrot slices
Aim: To carry out the energy and exergy analyses of drying chamber in a semi-industrial continuous band dryer
Experimental or simulation variable(s): $T=$50–70 °C, MFDA=0.61–1.83 kg/s, and FP=2.98 × 10–4–4.16 × 10–4 kg/s
Outcome: The exergy loss and exergy efficiency were found to be in the range of 0.66–14.15 kJ/s and 55.27–93.29%, respectively

Author(s): Cay et al. [58]
Dryer type: Industrial convective dryer
Product(s): Textile
Aim: To present a new model for the exergetic analysis of the convective drying of textiles at stenters and examine the variations of exergetic parameters for each chamber
Experimental or simulation variable(s): $T=$150 °C, different drying chambers (six chambers), and direct gas-heated and hot oil-heated stenters
Outcome: The exergy efficiency values of each chamber of the direct gas-heated were calculated to be 10.9, 14.9, 15.3, 12.2, 9.8, and 5.3, respectively. The total exergy destruction rate of the hot oil-heated was higher than that of the direct gas-heated

Author(s): Cay et al. [59]
Dryer type: Industrial convective dryer
Product(s): Textile
Aim: To investigate the effects of exhaust air humidity ratio, the residual moisture content of fabric outlet, and the temperature of the drying air on the exergy destruction and efficiency of stenters
Experimental or simulation variable(s): $T=$120–170 °C, the residual moisture content of fabric, drying chamber (six chambers), exhaust air humidity ratio, and direct gas-heated and hot oil-heated stenters
Outcome: The exergy efficiencies of the direct gas heated stenter and hot oil heated stenter were calculated to be varying from 8.5 to 17.5% and from 6.8 to 14.0%, at the surveyed drying conditions, respectively

Author(s): Utlu et al. [60]
Dryer type: Industrial dryer including spray dryer, vertical hot air dryer, and furnace
Product(s): Ceramic
Aim: To apply the energy and exergy analyses using the actual operational data over a period of 12 months
Experimental or simulation variable(s): Actual data varied with the drying time
Outcome: The exergy efficiency values for spray dryer, vertical hot air dryer, and furnace were in the range of 44.85–65.16%, 34.92–45.42%, and 12.73–16.41%, respectively

Author(s): Peinado et al. [61]
Dryer type: Rotary dryer
Product(s): Asphalt
Aim: To express the energy and exergy analyses of a rotary dryer employed in a hot mix asphalt plant for heating and drying of the aggregates in the mixture
Experimental or simulation variable(s): hot mix temperature (150–200 °C), solids humidity (1–7%), filler fraction in aggregates (5–20%), and exit air temperature (60–130 °C)
Outcome: The plant performed with energy and exergy efficiencies of 89% and 18%, respectively, at design conditions

Table 3 (*continued*)

Author(s): Kong et al. [62]
Dryer type: Coating paper machine predryer
Product(s): Paper
Aim: To conduct thermodynamic analysis to seek the possibility of improving energy efficiency
Experimental or simulation variable(s): Actual drying condition
Outcome: The results of the case study indicated an energy efficiency improvement of 7.3% and a specific energy consumption reduction of 4.6% with profitable investments

Author(s): Colak et al. [63]
Dryer type: Four step industrial dryer
Product(s): Pasta
Aim: To apply the exergy analysis of a four-step drying system in a pasta production line
Experimental or simulation variable(s): mass flow rates of hot water (1–3 kg/s), mass flow rates of pasta (200–400 kg/s), mass flow rates of drying air for each dryer (1–7 kg/s), boundary temperatures for dryers (≈ 30.5–40 °C), and dead-state temperature (15–30 °C)
Outcome: The exergy efficiency of drying process values varied between 0.25% and 5.27% from the predrying to the final drying section. The exergy efficiency of drying process value for the entire drying system was calculated to be 2.96%

Author(s): Prommas et al. [64]
Dryer type: Continuous belt system
Product(s): Glass beads
Aim: To analyze the combined multi-feed microwave-convective air and continuous belt system using the energy and exergy method
Experimental or simulation variable(s): air $T=$30–70 °C, $t=$70–420 min, with and without microwave power, and magnetron arrangement
Outcome: The exergy efficiency of dryer during hot air drying was profoundly higher than the microwave drying. While the magnetron arrangement did not lead to a significant difference in exergetic efficiency

resulted from the exergy destruction during hot water process and in air flow circuit lines. Improving the drying chamber's isolation and recycling the exhausted air was proposed as the solution for enhancing the incoming of industrial continuous drying. As well, the exergetic performance of whole system slightly decreased by dead-state temperature [55]. However, it must be noted that the application of the exergy concept often requires careful consideration of the choice of dead condition.

Cay et al. [53] indicated that the significant portion of input exergy exhausted to the environment by humid exhaust air of the stenter. The humidity ratio of the exhaust air should be feasibly elevated for increasing the exergy efficiency of drying process. This exhaust air was the major source of waste heat and provided a significant energy saving potential.

Ozgener [52], investigating the exergoeconomic analysis for the industrial pasta drying process, found that the highest energy losses and irreversibility in system took place on the drying cabin surfaces and the remaining system processes had a relatively low influence on the overall efficiency. The ratio of thermodynamic loss rate to capital cost was mathematically correlated with total exergy input, mass flow rate of drying air, and dead-state temperature. It exponentially decreased with the increasing total exergy input and the dead-state temperature, but increased with increasing the mass flow rate of drying air. However, developing an individual regression model for exergoeconomic parameter which reflects the effects of various drying parameters on thermoeconomic assessment might lead to a more comprehensive and deeper insight into the process.

Aghbashlo et al. [7,54] reported that the increasing drying air temperature decreased the exergy efficiency of continuous band dryer. It could be attributed to the drastic exergy loss and exergy leakage through the drying chamber to ambient resulted from insufficient insulation and airproofing. As well, the exergy efficiency increased with increasing drying air mass flow rate and decreasing feed mass flow rate. It must be noted that the exergy

analysis for overall drying systems based on drying process efficiency could potentially represent more meaningful and advantageous conclusions. The outflow exergy and exergy loss from dryer frame were the major sites of thermodynamic inefficiencies, showing that a large portion of the supplied thermal exergy was lost to ambient. Insulating the dryer frame, sealing the dryer body, designing and selecting the appropriate components, choosing the optimum drying condition, recycling the exhaust air, changing the hot air direction (upward or downward), and developing the multiple-pass and the multiple-stage dryers were suggested as ways to enhance the exergy efficiency of dryer. It is also mentioned that the uniforming air and temperature distributions inside the drying chamber by thermodynamics modification could result to an efficient and high exergy efficiency drying process.

Unlike with the observation of Ozgener and Ozgener [55], Cay et al. [57] found that the exergy efficiency of belt dryer and stenter linearly increased with increasing dead-state temperature. It can be concluded that the different expressions for the exergy efficiency of drying operation is the main reason for this diversity. However, the effect of dead-state condition on exergy efficiency of each drying processes and systems is exclusive and should be separately examined for different drying methods and equipments. As well, it was found that the increasing the exhaust air humidity ratio from dryer enhanced the exergetic efficiency of the drying process due to the productively utilizing of supplied exergy to drying chamber for water evaporation from products.

It was also concluded that the selection of a dead-state condition plays an important role in performing exergetic calculations because this will specify what kind of equilibrium will be created with the environment.

Incorporating a heat exchanger with the drying system can significantly augment the exergy efficiency of drying process as reported by Coskun et al. [56] for an industrial wood chips drying process. Generally, the energy efficiency of wood chips drying process was profoundly higher than the exergy efficiency, reflecting that the larger amount of provided exergy to drying drum destructed in the drying process. As well, the exergy efficiency decreased with outdoor temperatures while the energy efficiency increased. Moreover, the study could be extended with thermoeconomic assessment for each component and overall system to gain better insight of the exergoeconomic performance by identifying and ranking the components of the system with respect to their contribution to the overall exergy loss rate to capital cost. Subsequently, the system's optimization could be carried out again for retrofitting/re-designing high irreversibility components.

Cay et al. [58], investigating the exergetic performance of convective drying of textiles at stenters as well as variations of exergetic parameters for each chamber of the stenter, found that the exergy efficiency reduced significantly for last chambers due to the lower moisture evaporation during falling rate period. Nevertheless, the exergy efficiency of drying process was very poor. The combustion chamber and mixing unit of the direct gas-heated and the hot oil boiler of the hot oil-heated were the main components responsible for the higher exergy destruction rates. Furthermore, total exergy destruction and loss rates of the hot oil-heated were higher compared to those with the direct gas-heated. Thus, employing the low exergetic-destructive components is mandatory for improving the exergetic performance of drying systems.

Cay et al. [59] also conducted a parametric study using subsystem models. Increasing drying air temperature increased exergy efficiency, especially in the constant rate and second rate period of the drying. The humidity ratio of exhausting air was a decisive parameter for the emerging irreversibilites in drying process, and the higher air humidity ratio led to a profound reduction in exergy destruction rates. The higher irreversibility rate of overdrying was responsible for lower exergy efficiency by increasing fuel consumption. It could be attributed to the smaller amount of exergy utilized for moisture evaporation at second stage of drying.

Utlu et al. [60] investigated the energy and exergy analyses of an industrial ceramic dryer which composed of three stages including spray drying, vertical dryer, and furnace process using the actual operational data over a period of 12 months. Generally, the thermal efficiency of process was very poor because of the high heat losses especially at the vertical dryer and furnace. The exergy utilization for all stages was even worse than energy utilization due to the intense exergy destruction at high drying air temperature and considerable exergy loss at the vertical dryer and furnace. The system had a great potential for improvement from exergetic point of view. The low exergy efficiency suggested that substantial opportunities for better exergy utilization in drying industry still exist.

Peinado et al. [61] found that the exergetic efficiency of a hot mix asphalt plant was very poor and the humidities of the aggregates, filler content in aggregates, working temperatures, and ambient conditions parameters had an important effect on exergetic efficiency of plant. The exergetic efficiency of process was also lower than the exergy efficiency of system, as repeatedly reported by previous investigators. The majority of site exergetic inefficiencies were attributable to the high irreversibility of combustion and the high temperature difference between the combustion gases and the product. To attain efficient and effective use of fuel in combustion other ways of heating and drying should be evaluated.

Kong et al. [62] presented a new waste heat integration scheme based on the results of the energy and exergy analyses. The presented strategy positively decreased the amount of input exergy to drying system by 3.5%. The energy efficiency of drying systems was improved by 7.32%, while the exergy efficiency of drying systems reduced by 1.47%. This discrepancy might possibly be resulted from the diversity in exergetic efficiency definition for drying process and system. Therefore, for obtaining the meaningful results from the exergy analysis of drying systems and process the exegetic efficiency definition should be modified to the process efficiency associated with whole system's components and consequently exergoeconomic analysis.

Prommas et al. [64] reported that the exegetic performance of a combined multi-feed microwave-convective air and continuous belt drying system was significantly influenced by particle size, hot air temperature, and location of magnetron. The exergetic efficiencies of trays and chambers decreased in the beginning of drying process, and then reached to constant value toward to the end of drying time. It is noted that the authors did not present any theoretical correlation between microwave energy and corresponding exergy value. It is well documented that the application of microwave technology for drying of wet materials can reduce energy requirement compared with the other drying techniques. However, the sustainability of microwave drying process should be authenticated by exergy analysis of drying process and overall drying system.

Colak [63] investigated the effect of mass flow rate of hot water, mass flow rate of pasta, mass flow rate of drying air, and dead-state temperature on exergetic performance of four steps industrial pasta drying system. Increasing the mass flow rate of hot water, mass flow rate of drying air, and dead state-temperature decreased the exergy efficiency of all drying steps, while increasing the mass flow rate of pasta increased the exergy efficiency. The exergy efficiency was mainly affected by evaporation exergy. It was recognized that the lower amount of supplied exergy was effectively utilized for water evaporation and majority

of exergy was wasted through dryer frame, outlet air, and outlet product. Isolating the dryers and reusing the return hot water flows in the following drying sections for heating of drying air can be suggested as the solution for improving the exergetic performance of drying process.

3.3. Heat pump assisted drying systems

Heat pumps are facilities for elevating the temperature of low grade heat energy to a more useful level using a relatively small amount of high grade energy [65]. They have been known as energy efficient equipments when used in conjunction with drying operations [8]. The heat pump dryers has many advantages over conventional hot air drying including the ability to recover energy from the exhaust gas and the capability to control the drying gas temperature and humidity [8]. A heat pump drying system consists mainly of two subsystems: a heat pump system and a drying system. The design parameters for its drying chamber can be expressed as tray dryers or continuous dryers. The heat pump dryer can be categorized as air source, ground source heat, and chemical heat-pump drying systems [66]. As well, the type of working fluid (refrigerant) and compressor and evaporator parameters can be also mentioned as designing parameters of heat pump dryers.

As can be seen in Table 4, numerous investigations have been performed on exergetic assessments of heat pump drying systems. However, heat pumps may incur higher capital costs which should be evaluated by engineering and economical analyses.

Ceylan [67] and Ceylan et al. [72] presented the exergy analysis only for drying chamber of heat pump drying of timber and some perishable fruits. The exergy efficiency of drying chamber continually increased with drying time due to the continuous reduction in the moisture content of the product, leading to small exergy destruction and elevating the exergetic efficiency of drying chamber toward to the end of drying process. There was no difference between presented mathematical formulations with the previous works published for hot air tray dryers. In the absence of any appropriate equations for the exergy and economic analyses of heat pump system, it is very difficult to propose the heat pump systems as tool for increasing the exergy efficiency of drying chambers.

Kuzgunkaya and Hepbasli [68] studying the exergetic performance of laurel leaves drying in a vertical ground-source heat pump drying cabinet found that the exergy efficiency of both drying cabinet and drying process increased with increasing drying air temperature. The exergy efficiencies of dryer were quite higher than exergy efficiency of process. It was hypothesized that lowering the boundary temperature of drying chamber might lead to a decrease in exergy loss and hence an increase in exergy efficiency. In continuation of the first work, a full-detailed exergetic assessment of a ground-source heat pump drying system was presented by researchers [69]. The largest irreversibility of drying system was belonged to the condenser, followed by compressor and expansion valve. The results showed that the application of a more efficient compressor and fan might lead to an increase in exergetic efficiency and a decrease in input power.

In the similar work, the exergetic performance of single layer drying process of mint leaves in a ground source heat pump tray dryer was carried out by Colak et al. [70]. The exergy efficiency increased with increasing drying air temperature, dead-state temperature, and drying air velocity but decreased with increasing boundary temperature. Meanwhile, deducing the boundary temperature was proposed for rebating the exergy loss and elevating the exergy efficiency. It was determined that the dead-state temperature strongly affected the exergy efficiency

Table 4
Exergy analysis of heat pump drying systems and processes.

Author(s): Ceylan et al. [67]
Dryer type: Heat pump assisted tray-dryer
Product(s): Timber
Aim: To determine the energy and exergy performance of drying chamber
Experimental or simulation variable(s): T=40 °C, V=0.8 m/s, type of timber (pine and poplar)
Outcome: The exergy efficiency of drying chamber increased with drying time and was higher for pine compared with the poplar

Author(s): Kuzgunkaya and Hepbasli [68]
Dryer type: Ground-source heat pump drying cabinet
Product(s): Laurel leaves
Aim: To calculate exergetic efficiency of drying process and drying chamber
Experimental or simulation variable(s): T=40–50 °C, RH=16–19%, and V=0.5 m/s
Outcome: The exergy efficiencies of drying chamber and drying process were varied between 81.35–87.48% and 9.11–15.48%, respectively

Author(s): Kuzgunkaya and Hepbasli [69]
Dryer type: Ground-source heat pump drying cabinet
Product(s): Laurel leaves
Aim: To perform the exergetic analysis for different components of drying system and overall drying system
Experimental or simulation variable(s): T=45 °C, RH=16%, and V=0.5 m/s
Outcome: The exergy efficiency of drying process based on overall system analysis varied between 15.5 and 21.1% and at a dead-state temperature of 27 °C

Author(s): Colak et al. [70]
Dryer type: Ground source heat pump tray dryer
Product(s): Mint leaves
Aim: To compute the exergy efficiency of drying chamber
Experimental or simulation variable(s): T=40–50 °C, MFDA=0.01–0.05 kg/s, and RH=16%
Outcome: The exergy efficiency values were obtained to vary from 76.03 to 97.24% for studied condition

Author(s): Erbay and Icier [71]
Dryer type: Pilot-scale heat pump dryer
Product(s): Olive Leaves
Aim: To optimize drying condition based on exergy efficiency of drying chamber and product quality
Experimental or simulation variable(s): T=45–55 °C, V=0.5–1.5 m/s, and t=270–390 min
Outcome: Optimum operating conditions were found to be temperature of 53.43 °C, air velocity of 0.64 m/s, process time of 288.32 min and correspond responses were total phenolic content loss of 9.77%, total antioxidant activity loss of 44.25%, final moisture content of 6.0% and exergetic efficiency of 69.55%

Author(s): Ceylan [72]
Dryer type: PID-controlled heat pump assisted tray dryer
Product(s): Kiwi, avocado and banana
Aim: To study the energy and exergy analysis of drying tray
Experimental or simulation variable(s): T=40 °C and V=0.37 m/s
Outcome: The exergy efficiency did not show a clear trend with product type, while increased with increasing drying time

Author(s): Erbay et al. [73]
Dryer type: Pilot-scale heat pump belt conveyor dryer
Product(s): Olive leaves
Aim: To carry out the exergetic performance assessment of system's components
Experimental or simulation variable(s): T=45–55 °C and 0.5–1.5 m/s.
Outcome: Exergetic efficiencies of the drying of olive leaves were in the range of 67.45–81.95%

Author(s): Hepbasli et al. [74]
Dryer type: Heat pump conveyor dryer
Product(s): Plum
Aim: To present the exergoeconomic analysis for overall drying systems
Experimental or simulation variable(s): T=45–55 °C and V=1.5 m/s
Outcome: Exergy destruction rates to capital cost values were obtained to vary between 1.668 and 2.063 W/ USD at different drying air temperatures

Author(s): Catton et al. [75]
Dryer type: Isothermal heat pump dryer
Product(s): Assumptive
Aim: To compare a plate contact-type isothermal heat pump dryer with a conventional heat pump dryer using numerical simulation of exegetic performance

Table 4 (*continued*)

Experimental or simulation variable(s): $T=55$ °C, MFDA=1 kg/s, and RH=30 Outcome: The irreversibilities in condenser and product had a predominant share in the overall work requirement in the adiabatic mode. This irreversibility profoundly reduced in the isothermal mode. The compressor and throttle were the main components for reducing the overall irreversibility
Author(s): Gungor et al. [76] Dryer type: Gas engine heat pump dryer Product(s): *Foeniculum vulgare*, *Malva sylvestris* L. and *Thymus vulgaris* Aim: To perform the exergetic analysis of whole drying system Experimental or simulation variable(s): $T=45$ °C and $V=1$ m/s Outcome: The exergetic efficiency values were in the range of 48.24–51.28% for the overall drying system
Author(s): Gungor et al. [77] Dryer type: Gas engine heat pump dryer Product(s): *Foeniculum vulgare*, *Malva sylvestris* L. and *Thymus vulgaris* Aim: To perform the exergoeconomic analysis of whole drying system based on exergy, cost, energy and mass Experimental or simulation variable(s): $T=45$ °C and $V=1$ m/s Outcome: The thermodynamic loss rate to the capital cost was in the range of 0.06–0.19 MW/TL and 0.71–0.77 MW/TL for drying chamber a gas engine heat pump unit, respectively (TL: Turkish Lira)
Author(s): Gungor et al. [78] Dryer type: Gas engine heat pump dryer Product(s): *Foeniculum vulgare*, *Malva sylvestris* L. and *Thymus vulgaris* Aim: To carry out the exergoeconomic analysis of whole drying system based specific exergy cost Experimental or simulation variable(s): $T=45$ °C and $V=1$ m/s Outcome: The exergy cost for overall system was found between 9.087 and 11.554 US$/h

and therefore taking the ambient temperature as dead state is important for the exergy efficiency of known system.

Erbay and Icier [71], optimizing the drying cabinet operating conditions for drying of olive leaves in a pilot-scale heat pump conveyor dryer using RSM, found that the moderate drying temperature and time values and the lower air velocities led to lower exergy efficiency. It was expected that the increasing drying air temperature caused a reduction in exergy efficiency. Conversely, the excellent isolation and airtight led to an inverse result. However, the exergetic assessment of drying chamber cannot reflect the advantages of heat pump assisted drying systems over the commonly employed convectional drying systems.

Exergetic performance of a pilot-scale heat pump belt conveyor dryer was assessed by Erbay et al. [73]. In contrast with the energy utilization ratio, the exergetic efficiencies increased with decreasing drying air temperature and increasing drying air velocity. The highest relative irreversibility, fuel depletion ratio, and productivity lack belonged to the motor-compressor assembly, followed by the condenser, expansion valve, evaporator, drying ducts, drying cabinet and fan. The compressor, condenser, and expansion valve had a predominant share in the systems efficiency by considering exergetic factor values because of handling higher amount of exergy. It can be concluded the heat pump system had a profound effect on the total exergy destruction of whole drying systems. Thus, this suggests that for a more sustainable and environmentally–friendly heat pump drying systems, other types of heat pump systems should be examined by taking into account the economic, engineering, final product quality considerations.

The quantities of exergy, cost, energy, and mass method were employed by Hepbasli et al. [74] to the exergoeconomic analysis of heat pump dryer with its main components using exergy destruction and capital cost rates. The ratio of exergy destruction rates to capital cost values had a linearly ascending trend with drying air temperature and was minimum for drying duct. The highest values were obtained for the compressor, expansion valve, and heat recovery. The capital cost of heat pump system is the main determining and limiting factor in the applicability of this system for industrial drying systems. It is obvious that the conscious and planned endeavors are needed to improve exergy utilization in the heat pump drying systems.

In another study, the exergetic performance and the sustainability index values of a newly developed gas engine heat pump drying systems during dehydration of three different medicinal and aromatic plants were investigated through the Grassmann diagram to give quantitative information regarding the proportion of the exergy input dissipated in the various system components [76]. The gas engine unit significantly affected the efficiencies of the overall system because of its highest improvement potential rate and exergetic factor values. The expansion valve had the highest exergy efficiency values in the system. As well, drying chamber had an acceptable exergy efficiency due to an excellent insulation and airproof. The researcher also employed the exergoeconomic analysis for mentioned system based on the experimental data using exergy, cost, energy and mass and specific exergy cost analyses methods to find the effect of varying dead-state temperatures on exergoeconomic performance parameters for both drying system components and drying process [77,78]. In the first study, increasing dead-state temperature profoundly increased the exergy efficiencies of drying process and decreased the ratio of the thermodynamic loss rate to the capital cost. The exhaust air from heat exchanger, drying ducts, heat recovery from engine cylinder jacket, expansion valve, and gas engine were inefficient due to the overall system results and these components should be focused for improving the performance of system. Finally, the exergetic and exergoeconomic parameters were approximated using the linear and second-order mathematical models as a function of dead-state temperature. In the second study, the gas engine exergoeconomic parameters was not significantly influenced by the variation of ambient temperature, while this variation profoundly affected the condenser and drying chamber parameters. As previously explained, the capital cost of heat pump system is an important factor and therefore the comparative exergoeconomic studies are required to compare different drying systems. However, it was proved that exergoeconomic analysis can provide more comprehensive insight than exergy analysis, and the results obtained from the exergoeconomic analysis provided cost-based information, suggesting the potential locations for drying system improvement.

A numerical simulation of a plate contact-type isothermal heat pump dryer was applied to evaluate the energy efficiency improvement obtainable from this system compared with a conventional heat pump dryer [75]. The isothermal and adiabatic modes were considered for exergy analysis and the performance gain was calculated between 2 and 3 for isothermal mode. The condenser and product irreversibilities contributed much of the overall work requirement in the adiabatic mode. Also, the isothermal mode profoundly decreased this irreversibility, by about six-time per kg of water evaporated. It seems that the heat pump components have a predominant share in total exergy destruction of drying systems. Thus, exergoeconomic simulation and comparative study can manifest the suitability of heat pump systems for incorporating with industrial drying systems.

3.4. Fluidized bed drying

Fluidized bed drying are extensively employed drying method for the wet particulate and granular materials that can be fluidized, and even slurries, pastes, and suspensions that can be fluidized in beds of inert solids. The principal advantages of fluid bed drying emerge from good solids mixing, high rates of heat

and mass transfer, and easy material transport [79]. The fluidized bed dryer has many design parameters such as drying medium temperature variation, distributor structure and vessel geometry, capacity of dryer, type of heater (electrical, fuel-powered, etc.), mode of feeding (continuous or batch), etc. The published works regarding the exergy analysis of fluidized bed drying processes and systems are summarized in Table 5.

Syahrul et al. [80] conducted a parametric study to find the effects of inlet air temperature, fluidization velocity, and initial moisture content on both energy and exergy efficiencies. The exergy efficiencies of drying process were lower than the energy efficiencies due to irreversibilities which were not taken into consideration in energy analysis. The energy and exergy efficiencies of drying process also decreased towards to the end of drying process due to a decrease in moisture content of product. The exergy leaving drying system, exergy destruction, and exergy loss to ambient air through the column were cited as the major thermodynamic inefficiencies. It could be reduced by recycling the exhaust gas, diminishing the exergy destruction inside drying chamber, and avoiding the heat transfer across the boundary. In the second survey, the authors analyzed the fluidized bed drying process of large particles to optimize the input and output conditions based on the energy and exergy concepts [81]. The effect of hydrodynamic and thermodynamic conditions was examined on the energetic and exergetic performance of wheat and corn drying process. The thermodynamic efficiency of the fluidized bed drying had a falling form in conjunction with the moisture removal rate. The drying air temperature had a strong influence on thermodynamic efficiency of wheat drying process, while the drying air temperature did not show a profound effect on thermodynamic efficiency of corn drying process due to dependency of the diffusion coefficient to the temperature and moisture content of particles. The higher energy and exergy efficiencies were obtained for particles with higher initial moisture content. As well, the presented model precisely predicted the experimental results. Generally, it can be perceived that the exergy efficiency of fluidized bed drying process was relatively lower than the tray drying process. It is attributed to the higher amount of exergy supplied to drying chamber in fluidized bed dryer.

On a further research, Fortes [82] and Fortes and Ferreira [83] applied one-dimensional and lumped numerical solution of continuity, momentum, heat, mass, entropy, and exergy balance equations to find the effects of air relative humidity and air recirculation and bed height, drying air temperature, and fluidization velocity on energetic and exergetic performance of fluidized bed drying, respectively. The recirculation increased drying time but has a small effect on first and second-law efficiency. However, the bed height strongly affected the energy and exergy efficiencies. It can been seen that the exergy efficiency rapidly increased with time at initial stage of drying due to product heating-up, and reached a peak of maximum exergy efficiency, with further increase in time, the exergy efficiency continually decreased. The model successfully predicted exergy efficiency of drying process as a function of different drying parameters. However, the results of the model validation were not reported. Overlay, the coupling of continuity, momentum, heat, mass, entropy, and exergy balance equations had an acceptable potential for exergetic simulation of drying process.

Some unified non-dimensional experimental correlations were proposed for predicting the energy and exergy efficiencies of fluidized bed drying process by using hydrodynamics and thermodynamics parameters such as the inlet air temperature, the initial moisture content, and Fourier and Reynolds numbers [84]. The results showed a good agreement between the model predictions, non-dimensional correlations, and the available

Table 5
Exergy analysis of fluidized bed drying processes and systems.

Author(s): Syahrul et al. [80]
Dryer type: Laboratory fluidized bed dryer
Product(s): Wheat
Aim: To conduct the energy and exergy analyses are of the fluidized bed drying of moist materials
Experimental or simulation variable(s): T=40.2–60 °C, V=1.95 m/s, and RH=18.5–21.1%
Outcome: Exergy efficiency of drying process decreased with decreasing moisture content

Author(s): Syahrul et al. [81]
Dryer type: Laboratory fluidized bed dryer
Product(s): Wheat and corn
Aim: To carry out thermodynamic modeling of fluidized bed drying of moist particles
Experimental or simulation variable(s): T=40.2–60 °C, V=1.88–2.24 m/s, and RH=13.5–21.1%
Outcome: Increasing drying air temperature and drying air velocity decreased exergy efficiency of drying process

Author(s): Fortes [82]
Dryer type: Laboratory fluidized bed dryer
Product(s): Wheat
Aim: To address the modeling and evaluation of energy and exergy (availability) efficiencies related to fluidized bed drying by one-dimensional and lumped drying bed systems
Experimental or simulation variable(s): T=72 °C and V=1.2 m/s
Outcome: Exergy efficiency successfully simulated by presented model

Author(s): Fortes and Ferreira [83]
Dryer type: Laboratory fluidized bed dryer
Product(s): Wheat
Aim: To study the effect of bed height, drying air temperature and fluidization velocity using numerical simulation
Experimental or simulation variable(s): T=62.5 °C and V=1.2 m/s
Outcome: Second law efficiency successfully modeled using the introduced approach

Author(s): Inaba [84]
Dryer type: Experimental fluidized bed dryer
Product(s): Wheat and corn
Aim: To correlate the heat and mass transfer parameters on the energy and exergy efficiency of fluidized bed drying
Experimental or simulation variable(s): T=40.2–60 °C and V=1.88–2.24 m/s
Outcome: The energy and exergy efficiency successfully correlated with dimensionless moisture and temperature, Fourier number, and Reynolds number

Author(s): Nazghelichi et al. [79]
Dryer type: Experimental fluidized bed dryer
Product(s): Carrot cubes
Aim: To perform the energy and exergy analyses of drying chamber
Experimental or simulation variable(s): T=50–70 °C, bed depth=30–90 mm, and cube size=4–10 mm
Outcome: The exergy efficiency of drying chamber was found to be in the range of 10.3–70.7%

Author(s): Nazghelichi et al. [85]
Dryer type: Experimental fluidized bed dryer
Product(s): Carrot cubes
Aim: To model the energetic and exergetic parameters using static and recurrent ANN
Experimental or simulation variable(s): T=50–70 °C, bed depth=30–90 mm, and cube size=4–10 mm
Outcome: The energy and exergy of carrot cubes were predicted with R^2 values of greater than 0.95 and 0.97 using static and recurrent ANNs, respectively

Author(s): Nazghelichi et al. [10]
Dryer type: Experimental fluidized bed dryer
Product(s): Carrot cubes
Aim: To optimize ANN topology for predicting the energetic and exergetic parameters of drying chamber
Experimental or simulation variable(s): T=50–70 °C, bed depth=30–90 mm, and cube size=4–10 mm
Outcome: The energy and exergy of carrot cubes during fluidized bed drying were predicted with R^2 values of greater than 0.97 using optimal ANN topology

Author(s): Xiang et al. [86]
Dryer type: Heat pump-assisted fluidized bed dryer

Table 5 (*continued*)

Product(s): Wheat Aim: To compare the open air cycle, closed air cycle, and semiclosed air cycle heat pump-assisted fluidized bed dryer based on exergy concept Experimental or simulation variable(s): $T=70$ °C. Outcome: The exergy efficiency of the semiclosed approach was 29.2% and higher than two another approaches
Author(s): Assari et al. [87] Dryer type: Experimental fluidized bed dryer Product(s): Wheat Aim: To survey the energy and exergy analysis for batch fluidized bed dryer based on the Eulerian two-fluid model Experimental or simulation variable(s): $T=70$–100 °C and $V=4$–5 m/s Outcome: The presented methodology successfully estimated the exergetic parameters of drying process
Author(s): Khanali et al. [88] Dryer type: Experimental plug flow fluidized bed dryer Product(s): Rough rice Aim: To carry out the exergy analysis of rough rice drying process in laboratory-scale plug flow fluidized bed dryer Experimental or simulation variable(s): $T=50$–70 °C, MFP=46–135 g/min, weir height=0.05–0.1 m, and $V=2.5$ m/s Outcome: The energy and exergy efficiency values were found to be in the ranges of 7.97–31.32% and 4.18–12.00%, respectively

experimental results. Using the minimum fluidization velocity at the first drying stage and reducing the drying air temperature by decreasing product's water content were suggested as ways for augmenting the fluidized bed drying performance. The presented approach indicated an appropriate potential to model other drying technique.

The energy and exergy analyses of fluidized bed drying of carrot cubes at different drying air temperatures, bed depths, and square-cubed carrot sizes were surveyed by Nazghelichi et al. [79]. The exergy efficiency of dryer reached to a maximum value when higher drying air temperature, larger cube size, and shorter bed depth were utilized for drying experiment. As well, the exergy efficiency of dryer increased with increasing drying time. The exegetic performance of fluidized bed drying could be improved by shifting the fluidized bed to batch mode and incorporating the drying cabinet with microwave and infrared systems as heating source. The energetic and exergetic prediction of carrot cubes fluidized bed drying using the static and recurrent ANN was also presented [85]. The effect of ANNs model parameters was evaluated on the model performance and finally it was found that the recurrent ANN was better than the static ANN for this case. It was concluded that the ANN was the best option for automating and on-line controlling of fluidized bed drying process according to the exergetic performance of drying systems. In another survey, the RSM and genetic algorithm (GA) were integrated to optimize the ANN parameters for energetic and exegetic prediction of fluidized bed drying [10]. A multi-layer feed forward ANN was utilized to correlate the outputs (energy and exergy) to the four inputs (drying time, drying air temperature, carrot cubes size, and bed depth). The RSM was employed to establish the relationship between the ANN input parameters with the model estimation power and subsequently the GA applied for final optimization. The selected ANN topology had an acceptable precision for the energetic and exegetic perdition of fluidized bed drying. However, incorporating the ANN with drying system to maximize the exergy efficiency of drying process by considering the quality of dried product deserves further investigations.

Xiang et al. [86] probed the exergetic performance of open cycle, closed cycle, and semi-closed cycle of vehicle-mounted heat pump-assisted fluidization drying system driven by a diesel generator. The semi-closed approach provided a better energy savings under the same working conditions. However, the dryer driven by a diesel generator was not economically superior compared with the electric power. The detailed exergetic mathematical formulation was not presented for diesel engine and overall drying system in the work. As well, the economical computations have been performed based on energy concept. It is worth noting that the full detailed exergoeconomic calculation might lead to a quantitative grasp of process inefficiencies, a more comprehensive and deeper insight into the process and new unforeseen ideas for improvements.

Assari et al. [87] solved the governing equations for energetic and exergetic simulation of fluidized bed drying including continuity, heat and mass transfer, entropy generation using finite volume method. The reported results for energy and exergy efficiencies were similar to works performed by Fortes [82] and Fortes and Ferreira [83]. It is worth noting that two-fluid model has an acceptable accuracy to predict the energy and exergy by comparing the introduced non-dimensional correlations and one-dimension lumped solution and can be employed for other drying methods.

Khanali et al. [88] found that the exergy efficiency of rough rice plug flow fluidized bed drying process increased with decreasing drying air temperature and increasing feed mass flow rate and residual time. The exergy efficiency of drying chamber was significantly higher than the exergy efficiency of drying process. The exergetic analysis carried out only for drying process and chamber. It is motioned that the exergetic assessment for overall drying systems parallel with exergoeconomic analysis should be performed to attain further insights.

3.5. Solar drying

Solar-drying is the processing technology of vegetables and fruits in clean, hygienic and sanitary conditions to national and international standards with zero energy costs. It has many advantages such as saving energy and time, requiring less surface area, improving product quality, making the process more efficient and protecting the environment [89]. Solar dryer can be designed and classified based on the mode of air movement (natural or forced convection), type of absorber (thermal, photovoltaic-thermal, etc.), exposure to solar radiation (direct or indirect), structural arrangement of the dryer (open-air or structure-integrated), type of working fluid (air, water, and oil), hybrid with auxiliary systems (thermal storage, heat pump, geothermal or waste waters, dehumidification system, etc.) [90]. A number of studies have been performed on exergy efficiency of solar drying systems (Table 6).

Midilli and Kucuk [91] studied the energetic and exergetic performance of the drying process of shelled and unshelled pistachios using a forced convection solar drying cabinet. As expected, energy consumption of unshelled pistachio samples was higher than the shelled counterparts. An exergy loss equal to zero was obtained at the point where the exergetic efficiency was estimated as 100% when drying process discontinued in the system. The exergy efficiency decreased with increasing the cabinet temperature, while increased with progressing the drying time. The order, structure, and moisture content of products must be considered to reduce the exergy loss. The major part of exergy provided by solar collector was lost in exhaust air. Therefore, conscious plans for reusing the lost exergy might increase the exergetic performance of solar dryers to a large extent.

The energy and exergy analyses of the solar drying process of apricots in a rotary column cylindrical drying cabinet were undertaken by Akpinar and Sarsilmaz [92]. The highest exergy outflow and the most utilization of exergy were coincided with the maximum exergy loss in the system. The exergy efficiency of

Table 6
Exergy analysis of solar drying systems.

Author(s): Midilli and Kucuk [91]
Dryer type: Forced convection solar dryer
Product(s): Pistachio
Aim: To fulfill the energy and exergy analysis for solar dryer chamber
Experimental or simulation variable(s): T=40–60 °C, I=200–808 W/m^2, and V=1.23 m/s
Outcome: The exergy efficiency of drying cabinet was found between 15.65 and 100%

Author(s): Akpinar and Sarsilmaz [92]
Dryer type: Rotary column cylindrical solar dryer
Product(s): Apricots
Aim: To accomplish the energy and exergy analyses of the drying cabinet
Experimental or simulation variable(s): T=38–57.8 °C, I=632–950 W/m^2, V=2.3 m/s, and rotary speed=2.25 rpm
Outcome: The exergy efficiency of drying chamber varied between 0.77 and 22.65%

Author(s): Akpinar [93]
Dryer type: Forced convection solar dryer
Product(s): Parsley
Aim: To undertake the exergy analysis of drying cabinet
Experimental or simulation variable(s): T=50.5–64.3 °C, V=0.4 m/s, and I= 558.7–936 W/m^2
Outcome: The value of exergy efficiency was found to be in the range of 35.76–86.79%

Author(s): Tiwari et al. [94]
Dryer type: Greenhouse
Product(s): Fish
Aim: To develop an analytical expression for exergy efficiency
Experimental or simulation variable(s): Forced convection (T=36–55 °C, V=5 m/s and I=360–900 W/m^2) and natural convection (T=40–54 °C and I=160–600 W/m^2)
Outcome: The exergy of greenhouse solar drying process was found to be in range of 0.004–0.287% and 0.101–0.133% under natural and forced convection mode, respectively

Author(s): Celma and Cuadros [95]
Dryer type: Indirect natural convection solar dryer
Product(s): Olive mill wastewater
Aim: To perform the energy and exergy analysis for drying cabinet
Experimental or simulation variable(s): T=34–52 °C, I= 227–825 W/m^2, and V=0.60–0.76 m/s
Outcome: The exergy efficiency ranged from 53.24% to 100% during the first day, and from 34.40% to 100% during the second day

Author(s): Ozgener and Ozgener [96]
Dryer type: Solar greenhouse dryer
Product(s): With 30–32% of moisture content
Aim: To employ Dincer and Sahin's model for actual drying condition
Experimental or simulation variable(s): T=40–49 °C, I=0–700 W/m^2, and V=0.1–0.3 m/s
Outcome: The average exergy efficiency of drying process was obtained as 63–73%

Author(s): Akpinar [97]
Dryer type: Forced convection solar dryer
Product(s): Mint leaves
Aim: To carry out the energy and exergy analyses of drying chamber
Experimental or simulation variable(s): T= 51.5–66.3 °C, V=0.4 m/s, and I= 561.5–939 W/m^2
Outcome: Exergy efficiency varied between 34.760% and 87.717% for the cabinet

Author(s): Akbulut and Durmus [98]
Dryer type: Forced convection solar dryer
Product(s): Mulberry
Aim: To conduct the energy and exergy analyses of drying chamber
Experimental or simulation variable(s): Ambient temperature=28–45 °C, MFDA=0.014–0.033 kg/s, and I= 123.3–939 W/m^2
Outcome: The exergy efficiency varied between 21.3 and 93.3% for studied drying conditions

Author(s): Tambunan et al. [99]
Dryer type: Solar dryer equipped with sensible heat storage
Product(s): Unknown
Aim: To assess the sensible thermal storage for a solar drying system based on exergy analysis
Experimental or simulation variable(s): T=30.8–42.5 °C, I=120.8–949.6 W/m^2, different mass flow rates of the air
Outcome: The ratio of exergy loss reached an optimum value at a certain charging time and was influenced by number of transfer unit

Author(s): Tyagi et al. [100]
Dryer type: Solar dryer with evacuated tubes collector
Product(s): Unknown
Aim: To apply the energy and exergy analyses for solar collector
Experimental or simulation variable(s): T=71–125 °C, $I \approx$ 350–1120 W/m^2, and MFDA=$1.91\times10^{-4}-2.01\times10^{-4}$ kg/s
Outcome: The exergy efficiency of collector varied between 0.53 and 1.30%

Author(s): Boulemtafes-Boukadoum and Benzaoui [101]
Dryer type: Natural convection solar dryer
Product(s): Mint
Aim: To employ the energy and exergy analyses for drying chamber
Experimental or simulation variable(s): I=400 and 850 W/m^2 and V=0–0.2 m/s
Outcome: The exergy efficiency had a parabolic trend with drying time

Author(s): Chowdhury et al. [102]
Dryer type: Solar tunnel dryer
Product(s): Jackfruit leather
Aim: To calculate the energy and exergy efficiency of collector and drying chamber
Experimental or simulation variable(s): T= 43–58 °C and I= 100–600 W/m^2
Outcome: The exergetic efficiency of collector and the mean value of the exergetic efficiency of dryer was 32–69% and 41.42%, respectively

Author(s): Sami et al. [103]
Dryer type: Forced convection solar dryer
Product(s): Unknown
Aim: To simulate the energetic and exergetic performance of forced convection dryer based on dynamic mathematical model
Experimental or simulation variable(s): $T \approx$ 25–65 °C
Outcome: The minimums of total exergy efficiency were 32.3% and 47.2% on the first and second days, respectively

Author(s): Bolaji [104]
Dryer type: Direct, indirect, mixed mode solar dryer
Product(s): Unknown
Aim: To analyze the solar dryer chamber based on exergy concept
Experimental or simulation variable(s):
Outcome: Average exergetic efficiencies of 55.2%, 54.5% and 33.4% were obtained from mixed mode, indirect mode and direct mode systems, respectively

Author(s): Lamnatou et al. [105]
Dryer type: evacuated-tube air collector
Product(s): Carrot, apple, and apricot
Aim: To compute the exergy loss for drying chamber
Experimental or simulation variable(s): T=54.4–66.6 °C, I=950–1050 W/m^2
Outcome: Increasing drying air velocity increased the exergy loss and it was revealed that the exergy loss for the double-tray case was higher than the single-tray ones

Author(s): Panwar et al. [106]
Dryer type: –
Product(s): –
Aim: To list some papers about the exergy analysis of hot air and solar drying systems
Experimental or simulation variable(s): –
Outcome: The numerical results of exergetic analysis of hot air and solar drying systems were presented

Author(s): Bennamoun [107]
Dryer type: –
Product(s): –
Aim: To overview the different mathematical methods for modeling and calculating the energy and exergy efficiency of a solar drying system
Experimental or simulation variable(s):–
Outcome: The mathematical model for exergy analysis of solar drying processes and systems comprehensively reviewed

I: solar radiation.

drying chamber was significantly lower than the Midilli and Kucuk's study [91]. It could be related to the higher moisture content of apricots compared with pistachios which increased the exergy destruction in drying chamber and consequently

decreased the exergy efficiency. As well, the diversity in physical properties of products could led to this inequality.

Akpinar [93,97] found that the exergy efficiency of drying chamber was relatively high and major part of supplied exergy to dying chamber was vented through the outlet air. The improvement potential decreased with increasing drying time and ambient air temperature whereas the exergetic efficiency increased with increasing ambient air temperature. The exergy efficiency of dryer had an opposite trend with energy utilization ratio. Increasing the cabinet loading capacity, using multiple trays, recycling outlet air and using heat pumps can be suggested as ways for increasing the exergy utilization in solar drying.

In another survey, the energy analysis was employed to predict fish surface temperature, greenhouse room air temperature, and moisture evaporated during greenhouse drying of Prawn under natural and forced convection conditions [94]. The predicted values indicated good agreements with experimental data. As well, the investigator established an analytical expression for exergy efficiency. The exergy efficiencies under natural and forced convections were lower than the corresponding energy efficiencies. However, the exegetic performance of forced convection drying was better than the natural convection. It could be attributed to faster drying rate resulted from higher drying air velocity. Exergetic efficiency of a solar dryer may vary during successive days. Generally, it can be concluded that the small part of supplied exergy was fruitfully utilized for drying in solar drying procedure.

The higher exergy efficiency of drying chamber was also certified by Celma and Cuadros [95] in analyzing the exergetic performance of drying chamber during drying of olive mill wastewater using an indirect type natural convection solar dryer. Exergetic efficiencies decreased with increasing inlet air temperature due to a significant increase in exergy loss. Exergy loss showed a linear relation with energy utilization. The higher exergy efficiency computed for drying chamber manifesting that the availability of considerable amount of obtainable energy in the exhaust air. Using photovoltaic panel for air ventilating instead of natural convection and accordingly accelerating the drying rate by considering exergy efficiency of drying process and economic consideration behooves further surveys.

The proposed model by Dincer and Sahin [25] was employed for computing the exergy variation of solar greenhouses dryer by Ozgener and Ozgener [96]. Exergy efficiency of drying cabinet displayed a decaying linear correlation with the inlet temperature while a rising curvilinear trend with the drying time. Furthermore, increasing mass flow rate of drying air decreased the exergy efficiency due to the higher exergy loss of drying chamber. The exergy loss through drying cabinet played an important role in reducing exergy efficiency of drying chamber by increasing drying air temperature and drying air velocity.

Akbulut and Durmus [98] also reported that the exergy efficiency of drying chamber increased with increasing drying air mass flow rate in a forced convection solar dryer. As expected, reducing the difference between inlet and outlet temperatures of drying chamber elevated the exergetic efficiency. The exergetic efficiency of the drying chamber decreased as the energy taken from the solar collector was productively utilized for drying process.

The exergy analysis was utilized by Tambunan et al. [99] to assess the sensible thermal storage for a solar drying system. The role of heat transfer process on the simultaneous exergy charging and discharging of storage system in relation to the solar drying system was evaluated. The exergy loss ratio (the ratio of transferred exergy to the drying chamber) changed with the charging time and attained a minimum value at a certain charging time. The number of transfer units had a strong effect on the minimum exergy loss ratio and the time to reach this value. From exergetic point of view, the application of heat storage in a solar drying system was also recommended. It is worth noting that the exergy analysis for introduced systems in the combination with drying chamber as well as exergoeconomic analysis for overall system can reveal the suitability of this system for actual drying condition.

In another research with forced convection solar dryer developed using the evacuated tubes collector, the exergy efficiency of collector was much less than the energy efficiency and increased with increasing drying air mass flow rate [100]. The exergy efficiency of collector fluctuated during the drying experiments according to the sun radiation. However, the exergy efficiency of collector had a smoother fluctuation than the energy efficiency since the energy losses were more sensitive to the solar radiation. The authors did not report the results of the exergetic analysis for drying chamber and process. It can be concluded that the exergy efficiency of collector was very poor and further improvement is required to increase the exergetic performance of solar collectors.

Boulemtafes-Boukadoum and Benzaoui [101] reported that the exergy efficiency of drying cabinet indicated a descending behavior during the first 4.5 h and then represented a parabolic ascending pattern toward to the end of drying process. The magnitude of outlet exergy was very close to the inlet exergy manifesting that the smaller amount of generated exergy was fruitfully used for drying process.

The energy and exergy analyses of solar drying of jackfruit leather in a solar tunnel dryer displayed that the major portion of available energy was wasted in the collector and dryer, meaning that there was a significant potential to optimize the exergetic performance of dryer [102]. The exergetic efficiency of the collector had a linear relationship with the solar radiation. However, the authors did not consider the solar module employed for air ventilating in exegetic calculations.

A dynamic mathematical model for microscopic energy and exergy analyses of an indirect cabinet solar dryer was developed by Sami et al. [103]. The energy and exergy efficiencies were approximated using the predicted values for temperature and enthalpy of gas stream and the temperature, enthalpy, and moisture content of the drying solid along the time and the length of the solar collector and dryer. The employed dynamic mathematical model indicated a good potential for modeling, designing, and subsequent optimization of solar drying systems before any attempts to develop the equipments.

Bolaji [104] fulfilled an exergy analysis for three different types of solar dryer including direct, indirect, and mixed mode solar dryer. Author did not present an appropriate equation for the calculation of radiation exergy as well as collector exergetic analysis. However, an expectable result was reported that the exergy efficiency of drying chamber for mixed-mode approach was higher than the indirect and direct mode.

The energetic and exergetic analyses of a solar dryer with an evacuated tube collector during drying of apples, carrots, and apricots were presented by Lamnatou et al. [105]. An optimal collector surface area was found based on laws for minimum entropy generation. The effects of single and double-trays and several drying air velocities were studied on performance coefficients such as pick-up efficiency and exergy losses. The exergetic efficiency of collector, drying chamber, drying process, and overall systems were not computed. However, the presented methodology seems to be useful for designing and optimization of solar drying systems.

Panwar et al. [106] listed some studies regarding the energetic and exergetic performance assessment of solar dying systems and tray drying equipments. As well, the mathematical models employed for exergetic analysis of solar drying process and

systems were comprehensibly reviewed by Bennamoun [107]. It was concluded that the application of renewable energy systems in food industry can lead to a significant decrease in fossil and electrical energies demands and total production costs.

3.6. Freeze drying

The freeze drying may be employed for heat sensitive materials such as certain biological substances, pharmaceuticals, and foodstuffs, which may not be heated even to moderate temperatures in ordinary drying. In freeze drying, the water or another solvent is eliminated as a vapor by sublimation from the frozen products being dried in a vacuum chamber. The freeze drying has many advantages over hot-air drying method including little loss of favor and aroma [8]. The freeze drying composed of three steps including the freezing stage, the primary drying stage, and the secondary drying stage. The freeze dryers has many design parameters including cooling rate, freezing temperature and time at freezing stage, target product temperature, chamber pressure, and dryer capacity at primary drying stage, and heating rate and chamber pressure at secondary drying steps. The published works about the exergy analysis of freeze drying process are given in Table 7.

In an exergy analysis, Bruttini et al. [108] established mathematical expressions for analyzing the freezing stage of freeze drying process. Results indicated that the most significant exergy losses were belonged to reduction of the temperature of liquid phase from the temperature of the liquid solution at the start of freezing stage to the temperature of phase change (freezing) of water and the freezing of the free water at temperature of phase change (freezing). Another comprehensive mathematical model was developed by Liu et al. [109] for exergy loss analysis of freeze-drying process of beef. The majority part of exergy loss occurred in the primary drying, vapor condensation and vacuum pumping. Improving the vapor condensation, vacuum pumping, and their operating conditions can lead to a profound reduction in the exergy losses. However, the optimization of freeze drying process based on minimum exergy loss can be achieved by optimizing the surface temperature of material, chamber pressure, temperature of the cooling source at freezing stage, and temperature of the cooling source in the vapor condenser. Based on another mathematical model, the primary drying stage in freeze-drying of pharmaceuticals had a dominant share in exergy loss, followed by water vapor condenser, vacuum pump, and secondary drying stage [110]. Temperature and pressure gradients of water vapor and inerts in the material being dried and duration times of the primary and secondary drying stages had a predominant effect on the magnitude of the exergy inputs and exergy losses. The sustainability of freeze drying process can be significantly improved by reduction in the exergy loss of primary drying stage, the water vapor condenser, and the vacuum pump system.

Table 7
Exergy analysis of freeze drying process.

Author(s): Bruttini et al. [108] Dryer type: Freeze dryer Product(s): Mannitol Aim: To express a mathematical model for the exergy analysis of the freezing stage of freeze drying process Experimental or simulation variable(s): Aqueous Mannitol solution=5–15% weight and different cooling temperatures Outcome: The exergy loss significantly influenced by aqueous Mannitol solution and cooling temperature source
Author(s): Liu et al. [109] Dryer type: Freeze dryer Product(s): Beef Aim: To develop a comprehensive mathematical model for exergy analysis of freeze drying process Experimental or simulation variable(s): Temperature of cooling source of vapor condenser between −80 and −10 °C, chamber pressure between 100 and 600 Pa, surface temperature of material between 20 and 70 °C, and temperature of cooling source between −30 and −10 °C Outcome: The exergy consumptions in the primary drying, vapor condensing, vacuum pumping, freezing, and secondary drying were 35.69, 31.76, 23.29, 3.56, and 5.71% of the total exergy loss, respectively
Author(s): Liapis and Bruttini [110] Dryer type: Freeze dryer Product(s): Vials Aim: To develop the mathematical expressions for determining the exergy inputs and exergy losses in the primary and secondary drying stages, water vapor condensing, and vacuum pumping Experimental or simulation variable(s): Temperature of the cooling source of the condenser=230 K, lowest temperature of ice cooled down by the condenser =235 K, and lowest temperature of inerts cooled down by the condenser=239 K, inlet pressure of the vacuum pump system=5.07 Pa, exhaust pressure of the vacuum pump system=1.01325×10^5 Pa, theoretical pumping speed of vacuum pump system=0.09 m^3/s Outcome: The exergy loss in primary drying, water vapor condensing, vacuum pumping, and secondary drying stages were 42.58, 33.08, 19.04, and 5.30% of total input exergy, respectively

3.7. Spray drying

Spray drying has become the most important technique for dehydrating a liquid or slurry such as milk, coffee and egg powders, and is extensively used in various fields of chemical, biochemical, agricultural, food, polymer, pharmaceutical, ceramics, and mineral processing industries. The spray drying process composed of following stages: (a) pumping liquid to the atomization device; (b) atomizing the liquid by using nozzle such as the rotary disc atomizer, pressure nozzle, pneumatic nozzle, and ultrasonic nozzle; (c) drying of generated droplets in hot drying media; and (d) separating the dried particles from exhaust air [8]. Drying medium temperature, drying medium mass flow rate, feed mass flow rate, nozzle parameters, drying media (air, nitrogen, etc.), chamber shape, air-droplet contact systems, powder and air discharge systems, etc., are the main parameters affecting the spray dryers' design and accordingly the attributes of produced powder [8]. Recently, the exergy analysis of spray drying systems and processes has been investigated by several researchers (Table 8).

In an industrial milk drying system studied by CFD modeling, large particles produced more entropy per unit mass on dry basis. Increasing inlet mass flow rate generated more entropy than increasing air temperature for reducing the moisture content of product powders. The entropy generation rate due to heat transfer between two phases was the most important component in total entropy generation rate followed by the entropy generation rate to mass transfer between two phases, gas phase viscous dissipation, gas phase heat transfer, and gas phase mass transfer [111]. The exergy loss through drying chamber was ignored for exergetic efficiency calculation of drying chamber. However, the previous experimental investigations showed that the exergy loss due to heat loss has a predominant share in overall exergy loss and accordingly on exergy efficiency of drying systems. Nevertheless, the presented methodology can be employed for simulating and optimizing other kinds of spray dryers based on exergy concept.

Aghbashlo et al. [112] modified the model proposed by Dincer and Sahin [25] according to spray dryer characteristic in order to write the mass, energy and exergy balance for fish oil microencapsulation process. The exergy efficiency of drying process was very poor indicating that the spray drying is an exergy-destructive process. Exergy efficiency decreased by increasing drying air temperature, drying air mass flow rate, and spraying air

Table 8
Exergy analysis of spray drying systems and processes.

Author(s): Jin and Chen [111]
Dryer type: Industrial spray drying system
Feed(s): Milk
Aim: To compute the entropy generation rate from the computational fluid dynamic modeling using the transient multi-phase flow
Experimental or simulation variable(s): Simulation with different drying air conditions and feed properties
Outcome: Generally, increasing drying air temperature and drying air mass flow rate decreased exergy efficiency of drying chamber

Author(s): Aghbashlo et al. [112]
Dryer type: Laboratory spray dryer
Feed(s): Fish oil emulsion
Aim: To fulfill the exergy analysis for spray drying process of fish oil microencapsulation
Experimental or simulation variable(s): T=140–180 °C, spraying air flow rate=600–800 l/h, aspirator rate=55–75%, and peristaltic pump rate=5–15%
Outcome: The exergy efficiency varied between 1.64 and 14.43%

Author(s): Erbay and Koca [113]
Dryer type: Pilot scale spray dryer
Feed(s): White cheese
Aim: To evaluate the pilot scale spray dryer based on energetic, exergetic, and exergoeconomic analyses
Experimental or simulation variable(s): T=160–230 °C and atomization pressure=294.2–588.4 kPa
Outcome: Exergetic efficiency of drying process was found to vary between 2.66 and 6.00%

Author(s): Aghbashlo et al. [114]
Dryer type: Laboratory spray dryer
Feed(s): Fish oil emulsion
Aim: To conduct the energy and exergy analyses for fish oil microencapsulation
Experimental or simulation variable(s): T=140–180 °C, spraying air flow rate=700 l/h, aspirator rate=65%, peristaltic pump rate=10%, and five different emulsions
Outcome: The energy and exergy efficiency values for drying were found to be in the ranges of 7.48–8.54% and 5.25–7.42%, respectively

Author(s): Aghbashlo et al. [115]
Dryer type: Laboratory spray dryer
Feed(s): Fish oil emulsion
Aim: To optimize the drying condition based on quality and exergy concept
Experimental or simulation variable(s): T=140–180 °C, aspirator rate=55–75%, peristaltic pump rate=5–15%, and spraying air flow rate=700 l/h
Outcome: The optimal drying condition for microencapsulation of fish oil was: inlet drying air temperature=177.23 °C, aspirator rate=63.93%, and peristaltic pump rate=14.04% yielding exergy efficiency of 8.10% and encapsulation efficiency of 79.14%

Author(s): Aghbashlo et al. [116]
Dryer type: Laboratory spray dryer
Feed(s): Fish oil emulsion
Aim: To optimize the emulsion preparation procedure based on quality and exergy concept
Experimental or simulation variable(s): T=160 °C, aspirator rate=65%, peristaltic pump rate=10%, spraying air flow rate=700 l/h, aqueous phase content=70–90%, oil concentration with respect to total solids=10–30%, emulsification time=5–15 min
Outcome: The optimal condition based on quality and exergy concept was 87.1% aqueous phase content, 10.8% oil proportion in total solids, and 13.2 min emulsification time

Author(s): Aghbashlo et al. [117]
Dryer type: Laboratory spray dryer
Feed(s): Fish oil emulsion
Aim: To model the exergetic performance of spray drying process using ANN
Experimental or simulation variable(s): T=140–180 °C, spraying air flow rate=600–800 l/h, aspirator rate=55–75%, and peristaltic pump rate=5–15%
Outcome: The selected ANN topology predicted exergetic parameters of spray drying process with R^2 values greater than 0.98

Author(s): Erbay and Koca [118]
Dryer type: Pilot scale spray dryer
Feed(s): White cheese
Aim: To perform the exergy analysis for overall spray drying system
Experimental or simulation variable(s): T=160–230 °C and atomization pressure=294.2–588.4 kPa
Outcome: The exergetic factor of the compressor (26.54–36.71%) was highest, followed by heaters (22.57–33.35%) and drying cabinet (12.72–20.66%)

flow rate but increased with increasing feed mass flow rate. The exergy efficiency was profoundly influenced by exergy of drying air and exergy of spraying air. Therefore, it is necessitated to use lower feasible drying temperatures and spraying air flow rates by considering the final products quality.

Erbay and Koca [113] indicated that the exergy efficiencies were below than the energy efficiencies for pilot scale spray dryer during white cheese drying. The exergy efficiency of drying process decreased with increasing dead-state temperature. Generally, improvement potential rate increased with increasing the atomization pressure and inlet and outlet drying air temperatures. However, the improvement potential rate was significantly influenced by atomization pressure. In another study, Erbay and Koca [118] presented a full detailed exergetic analysis of whole pilot-scale spray dryer system. The compressor had an important effect on overall input exergy followed by the heaters and drying cabinet. It can be concluded that the air compressing for liquid atomization is an important factor not only in the final product quality but also in the exergy analysis of drying systems. However, the final product quality must be considered during the selection of optimal dryer operational conditions. Lower exergy efficiencies than energy efficiency were also reported by Aghbashlo et al. [114] for fish oil microencapsulation process by spray drying at various inlet drying air temperatures and different single and composite wall materials. They attributed this observation to exergy destruction based on second law of thermodynamics. An integrated approach by coupling RSM and GA to optimize the spray dryer operational condition and emulsion preparation procedure for the production of fish oil microcapsules showed that the combining of final product attributes with the exergy analysis hindered the energy loss by retaining the quality of finished microcapsule to a large extent [115,116]. However, this approach should be further investigated by other optimization technique and considering the economic value of utilized exergy. Finally, in an attempt to predict the exergetic performance of fish oil microencapsulation process by spray drying, Aghbashlo et al. [117] applied a feedforward ANN. The selected ANN topology accurately predicted the exergetic parameters of spray drying process and could be applied to determine the exergy efficient drying conditions to achieve a sustainable spray drying process. It is worth noting that the additional surveys are needed to incorporate the spray dryer systems with ANN models to control and optimize dryer's operational conditions in real-time.

3.8. Vacuum drying

Vacuum drying is a procedure of heat-sensitive wet material dehydration in a reduced pressure environment by reducing the boiling point of the liquid to be removed [8]. There are many parameters affecting the vacuum dryer performance such as drying temperature, chamber pressure, heating source, and surface area. Recently, Dikmen et al. [119] fulfilled an exergy analysis for vacuum drying chamber of pine timbers using PLC controlled vacuum dryer at drying air temperature of 40–60 °C, chamber pressure of 60–80 kPa, and product residual time of 5–15 min. The exergy efficiency of system had a high value at lower drying temperature, higher chamber pressure, medium residual time. Vacuum drying has many advantages over the other drying methods including lower energy consumption, faster drying, less product damage, handling the toxic materials, and recovering the evaporated liquid. However, the capital of vacuum dyer is relatively high. Therefore, the comparative exergoeconomic studies are needed to evaluate the overall exergetic performance of different drying systems and employ conscious strategy to save exergy and environment during vacuum drying process.

3.9. Flash drying

Flash drying is a pneumatic drying process suited to dry products requiring the removal of free surface moisture due to short thermal contact between the conveying air and the solids. The main important components of simple flash drying system can be the gas heater, the wet material feeder, the drying duct, the separator, exhaust fan, and a dried product collector [8]. Orhan et al. [120] performed the energy and exergy analyses for the drying step of the copper–chlorine cycle for hydrogen production in a flash dryer at different evaporator drying temperatures and evaporator inlet temperatures. Generally, increasing the evaporator inlet temperature increased the exergy efficiency of drying chamber, whereas increasing the evaporator drying temperature acted vice versa. The results of the energy and exergy analyses can be used for exergoeconomic analysis and optimization in future studies for reducing product costs and environmental concerns.

4. Conclusions and future trends

Exergy analysis has been used in a variety of applications for analyzing and optimization of energy systems and could help to overcome problems in many fields including energy efficiency improvement, energy resource usage, and find the causes, locations, and magnitude of inefficiencies. The interest for exergy analysis of drying systems is growing due to lower thermal efficiency of drying systems, higher price of fossil fuel and electricity, greenhouse gas emission from drying systems, and subsequently global warming. This review paper dealt with the most important applications of exergy analysis in drying technology. This exergetic analysis is still being developed but the advantages of using this analysis are obvious. Strengths of the exergy analysis include the appropriate accounting of the loss of availability of heat in a drying system using the conservation of mass and energy principles together with the second law of thermodynamics for the goals of design, analysis, and optimization. It has other advantages regarding the efficiency, losses and performance for drying systems and provides more meaningful and useful insights than the energy analysis. As well, the thermodynamic and economic values of the operation of drying systems could be correctly reflected and the capability to design more efficient drying systems by reducing inefficiencies could be actually revealed through the exergy analysis [11,13]. Therefore, the exergy analysis has a big potential to enter drying technology far away from energy analysis, kinetics studies, and rational heat and mass transfer simulation.

Literature survey showed that the exergy analysis has been already applied for few number of drying systems. The future researchers are encouraged to present exergy analysis for other drying system and find methods to increase the exergy efficiency of drying systems. Reusing the exhaust air, incorporating the drying systems with heat recovery system (heat exchanger, heat pump, mechanical vapor recompression, etc.), upstream dewatering to reduce initial moisture content, avoiding the overdrying, applying the electromagnetic wave energy (e.g., infrared and high frequency), per-treatment of material being dried, changes of material structure prior to or in the course of drying, insulating the drying chamber to avoid heat loss to environment, employing the combined heat and power system, using the multi-stage drying systems, pulse combustion drying technique, etc., could be used as ways for increasing the exergy efficiency of drying process.

Experimental exergy analysis is a time-consuming process, imposes a lot of costs due to instruments charge, and involves measurements errors because of sensors precision. Exegetic simulation of drying process by using the continuity, mass, momentum, energy, entropy-generation, and exergy balance equations has numerous advantages such as reducing the costs and times. Designing, constructing, examining, redesigning, reconstructing, and reexamining of drying systems can be an expensive and time-consuming project. Simulations contain the designing/redesigning phase out of the loop by applying the model already established in the design phase. Also, it is worthy to note that the time of simulation testing is cheaper and faster than performing the multiple tests of the design. The other biggest advantage of a simulation is the level of detail that investigator can get from a simulation. A simulation can provide researchers optional results that are not experimentally measurable due to technological limitation. On the other word, investigator can set the simulation to run for as many desirable time steps and at any optional level of detail. However, the numerical simulation requires sophisticated software and high computational efforts when compared to experimental analysis due to simultaneously solving of governing equations. Fortunately, with the current rate of the computer advancements, the associated problems with numerical simulations will be significantly reduced within the next few years. It seems that there is a lack of simulation works in field of exergetic evaluation of drying systems. The next investigators are encouraged to develop numerical equations for exergetic performance of different drying processes using the conversation and entropy production equations.

It is suggested to control drying systems based on exergy concept. By using the exergy analysis, operational control policies can be constructed that minimize the irreversibilities occurring in the drying operations, thus enhancing the efficiency of energy utilization in drying process. For example, by on-line calculation of exergetic performance, it is possible to set dryer operational condition to an efficient one during drying process. Also, the amount of air recirculated to systems can be on-lineally computed and controlled by exergy of exhausting air. Recently, growing attention has been given to control the drying systems using artificial intelligent systems. It seems that the combination of exergy concept through artificial intelligent paradigms might be one of the interesting fields for future investigators. On the other hand, increasing the sustainability of processes may negatively influence the quality of dried products especially food material and even deteriorate them. One interesting vision for the future would be to have fully automated drying systems to monitor and control the exergetic performance of dryers and the quality of dried product simultaneously.

In recent years, many investigators presented the exergy analysis for renewable drying systems such as solar drying systems. However, most of published works have presented the exergy analysis for demonstration projects. Based on authors' best knowledge, there is no information about the exergy application for industrial renewable drying systems. In future work, the exergetic performance assessment of more kinds of the renewable drying systems should be explored, such as solar drying system with thermal storage, hybrid with geothermal or waste waters, solar drying system with photovoltaic, solar drying system with heat pump, and solar-assisted dehumidification system. It is mentioned that the current trends towards to higher cost of fossil fuels, uncertainty regarding the future cost and availability, and environmental impact of fossil-fueled and electricity-powered drying systems have caused the increasing attention to utilization of renewable energy for drying process. Exergy analysis have been employed by many investigators to recognize the effect of process condition on exergy efficiency of drying systems and process, whereas limited works have been reported regarding the exergoeconomics of drying systems and

processes. It is worth nothing that the results given by exergoeconomic analysis are very meaningful and conceptual than the exergy analysis. More researches are necessitated to integrate the exergoeconomic analysis with the quality of dried products using the optimization and controlling tools to empower the energy savings, to reduce the environmental impacts as well as to obtain acceptable products.

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